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The mental representations underlying naval operations

Ginette Boudreau

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Abstract

The objective of this study is to review relevant theories and research pertaining to the fundamental mental representations that are common to humans in general and, in particular, to naval operations. The review will focus on the mental representations of the Operations Room (OR) team aboard the Halifax-Class Frigate (HCF). We will specify the structural, organizational, and functional properties of these mental representations. The practical aim of the review is to provide recommendations concerning the design of the tactical displays of the air, surface, and subsurface warfare areas.

The integration of relevant theories and research has enabled us to formulate the principle hypothesis according to which the OR team constructs three categories of mental models: physical mental models of the physical environment (such as warfare areas), shared mental models of the social environment (own and enemy units), and conceptual mental models of discourse among own and enemy units. We have based this hypothesis on the assumption that the OR team must represent and reason about the physical environment, the social environment, and discourse among own and enemy units. The results of this review suggests that all three categories of mental models are important for the OR team members. Tactical displays should thus support each category of mental models to provide the best cognitive fit, that is, to accurately match the mental representations of the OR team members.

Résumé

L'objectif de cette étude est d'intégrer les théories et les recherches pertinentes concernant les composantes de la représentation mentale qui sont communes aux humains en général, et en particulier, aux opérations navales. La revue de la littérature se concentre sur les composantes de la représentation mentale de l'équipe de la chambre d'opérations (ChO) de la frigate de patrouille canadienne. Nous allons déterminer les propriétés structurales, organisationnelles et fonctionnelles de cette représentation mentale. Le but pratique de cette revue de la littérature est de produire des recommandations concernant la conception des systèmes informatiques tactiques des milieux de querres aériens, navals, et terrestres.

L'intégration des théories et des recherches pertinentes nous a permis de faire l'hypothèse principale que les membres de l'équipe de la ChO construisent trois catégories de modèles mentaux: des modèles physiques, des modèles communs de l'environnement social, et des modèles conceptuels du discours entre les unités alliées et les unités ennemies. Chaque catégorie comprend différents types de modèles mentaux. Nous avons fondé la première hypothèse sur le fait que l'équipe de la ChO doit réfléchir et raisonner à propos de l'environnement physique, de l'environnement social, et du discours entre unités alliées et ennemies. Les résultats de cette étude suggèrent que les trois catégories de modèles mentaux sont importantes pour l'équipe de la ChO. Les systèmes informatiques tactiques devraient donc soutenir les trois catégories de modèles mentaux ainsi que leurs différents types.

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Executive summary

Mental representations are common to all human beings. They underlie the human capacity to think, remember events, reason, and take decisions. Our capacity to think depends on the existence of mental representations. The objective of this study is to review relevant theories and research pertaining to the nature of the mental representations that may underlie naval operations. The review will focus on the mental representations of the Operations Room (OR) team aboard the Halifax-class frigate (HCF). We will focus on the fundamental mental representations that are common to humans in general and, in particular, to the OR team. We will specify the structural, organizational, and functional properties of these mental representations. The aim of the review is to provide recommendations regarding the design of the tactical displays of the air, surface, and subsurface warfare areas. Improvements to the design of tactical displays are part of the HCF upgrade.

The OR team must manage and monitor vast amounts of stimuli (data and information, that is meaningful data) coming into the OR position especially in the littoral context. The OR team members are required to understand and represent stimuli that they perceive from the physical environment, the social environment, and discourse among own and enemy units. Theories and research on mental representations suggest that humans store information in long-term memory and in short-term memory. Humans store information in long-term memory according to a hierarchical structure of knowledge. The hierarchical structure groups objects within types, types within categories, and categories within supercategories. Cognitive scientists argue that schemas and mental models represent information in long-term memory according to a hierarchical structure.

However, humans construct mental models to represent information in real time in short-term memory. We have made the hypothesis that the OR team constructs three categories of mental models: physical mental models of the physical environment (such as warfare areas), shared mental models of the social environment (own and enemy units), and conceptual mental models of discourse among own and enemy units. We have based this hypothesis on relevant theory, research, and on the results of a cognitive task analysis that suggests that the OR team must represent and reason about aspects of the physical environment, the social environment, and discourse among own and enemy units. The results of this review suggests that all three categories of mental models are important for the OR team members. Tactical displays should thus support each category of mental models to provide the best cognitive fit, that is, to accurately match the mental representations of the OR team members. In the last section, we provide research issues and recommendations based on the theories and research that we have covered in this literature review. The recommendations aim at improving the design of tactical displays of the HCF OR. The recommendations aim at supporting the three categories of mental models that the OR team would construct during naval operations: physical mental models, conceptual mental models, and shared mental models.

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Sommaire

La représentation mentale est commune à tout être humain. Cette structure cognitive est sous-jacente à notre capacité de penser, se souvenir d'événements, de raisonner, et de prendre des décisions. Notre capacité de penser dépend de l'existence de la représentation mentale. L'objectif de cette étude est d'intégrer les théories et les recherches pertinentes concernant la nature de la représentation mentale sous-jacente aux opérations navales. La revue de la littérature se concentre sur les différents aspects des représentations mentales de l'équipe de la chambre d'opérations (ChO, Operations Rooms team) de la frigate de patrouille canadienne (soit le Halifax-class Frigate, HCF). Nous allons nous concentrer sur les propriétés de la représentation mentale qui sont communes aux êtres humains en général et en particulier, à celles qui sont propres à l'équipe de la chambre d'opérations. Nous allons déterminer la structure, l'organization et les propriétés fonctionnelles de cette représentation mentale. Le but pratique de cette étude est de produire des recommandations concernant la conception des systèmes informatiques représentant les théâtres de guerre aériens, terrestres, et sous-marins. Les améliorations faites aux systèmes informatiques tactiques constituent une partie importante des transformations apportées à la frigate de patrouille canadienneLa revue de la littérature se base sur la compréhension des processus cognitifs qui sont utilisés par l'équipe ChO. L'équipe ChO doit gérer un nombre important de stimuli (Soit des données et de l'information, c'est-à-dire, des données ayant de la signification) provenant de la ChO, surtout dans le contexte des guerres littorales. Les membres de l'équipe ChO doivent comprendre et représenter les stimuli provenant de l'environnement militaire. Cet environnement comporte des propriétés de nature physique, sociale et linguistique, chacune pouvant se rapporter aux rapports entre les unités alliées et les unités ennemies.

Les théories et les recherches portant sur la nature de la représentation mentale suggèrent que les humains enregistrent de l'information en mémoire à long-terme et en mémoire à court-terme. L'information en mémoire à long-terme est organisé suivant une structure hiérarchique de connaissance. La structure hiérarchique groupe les objets à l'intérieur de types plus abstraits. Les types sont à leur tour organisés en catégories, et les catégories sont organisées en supercatégories. Les scientifiques de la cognition stipulent que les humains construisent des schémas et des modèles mentaux pour représenter l'information en mémoire à long-terme. Toutefois, les humains construisent des modèles mentaux pour représenter de l'information en mémoire à court-terme. Nous avons fait l'hypothèse que les membres de l'équipe ChO construisent trois catégories de modèles mentaux: des modèles physiques, des modèles communs de l'environnement social, et des modèles conceptuels du discours entre les unités alliées et les unités ennemies. Nous avons fondé cette hypothèse sur le fait que l'équipe ChO doit réfléchir et raisonner à propos de l'environnement physique, de l'environnement social, et du discours entre unités alliées et ennemies. Les résultats de cette étude suggèrent que les trois catégories de modèles mentaux sont importantes pour l'équipe ChO. Les systèmes d'information tactiques devraient donc soutenir les trois catégories de modèles mentaux. Dans la dernière section, nous proposons des recommandations et des questions de recherche basées sur les théories et les expériences que nous avons analysées dans cette revue de littérature. Les recommandations visent à améliorer la conception des systèmes informatiques de la ChO de la frigate de patrouille canadienne. Les recommandations visent à soutenir les trois catégories de modèles mentaux que l'équipe de la ChO doit construire durant les opérations navales: les modèles physiques, les modèles conceptuels, et les modèles communs de l'environnement physique et du discours entre les unités alliées et ennemies.

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1. Introduction

1.1 Objectives and scope of the review

The objective of this study is to review relevant theories and research pertaining to the mental representations that may underlie naval operations in the context of single-ship operations. The review will focus on the fundamental mental representations that are common to humans in general and, in particular, to the mental representations of the Operations Room (OR) team aboard the Halifax-Class Frigate (HCF). The Command row in a HCF includes tactical displays for the Commanding Officer (CO), the Operations Rooms Officer (ORO), the Sensor Weapons Controller (SWC), and the Assistant Sensor Weapons Controller (ASWC). Members of the Command row have the main responsibility of constructing complex mental representations in support of situation awareness, reasoning, and decision making. These cognitive processes depend on integrated mental representations. Without a proper understanding of a tactical situation, accurate situation awareness and decisions cannot be reached to deal with the tactical situation.

Despite the crucial importance of mental representations, very few studies (Matthews, Webb, & Bryant, 1999a, b) have addressed the nature of the mental representations that may underlie naval operations. This review is intended to address this issue as well as determining the theoretical issues that scientists should investigate to build a bridge between research on mental representations and naval operations to provide recommendations concerning the design of the tactical displays of the air, surface and subsurface warfare areas.

In the situation of warfare, uncertainty and possibilities are the state of affairs. A major problem that military personnel have to deal with is to reduce this uncertainty and the number of possible state of affairs in order to achieve a situation where they can take the most likely course of action. During Maritime Operations, military officers have to think and reason about possibilities regarding the nature of the tactical situation. Such processes occur, for example, during operational planning where commanding officers must consider the enemy's possible courses of action and compare them to their own possible courses of action. How do naval personnel deal with uncertainty and the possibilities that this uncertainty generates? In light of present knowledge in cognitive science, we will make the hypothesis that naval personnel think and reason about uncertainty and possibilities using logic as a possible process. We will base this hypothesis on relevant cognitive theories and research and on the fact that the notions of uncertainty and possibility are logical-mathematical notions. Mathematical logics have envisioned the concepts of uncertainty and possibility from different logics, for example classical logics and non-classical logics. Cognitive theorists have also used different formalisms from mathematical-logic to account for the ways in which humans think and reason about uncertainty and their implied possibilities.

Cognitive theorists have followed two main approaches in the evolution of logic to account for aspects of human thinking and reasoning whether with uncertainty or certainty if that is possible. One approach is based on a classical logic (the proof-theoretic approach in logic) and is represented by the orthodox family of Formal Rules theories. The other approach, which represents new formalisms in non-classical logics (for example, the model-theoretic approach in logic, non-monotonic logic, and metalogic), is epoused by the Mental Models theory. Although

fascinating and worthy of discussion, we will not enter into the logical formalisms underlying the cognitive theories of human thinking and reasoning. However, we will introduce the theories at their surface level and present the wealth of the empirical support that they have received regarding the existence of fundamental cognitive structures. The review does not purport to be a universal theory of human cognitive structures but rather it considers the theories that have provided, over the past 20 to 60 years, empirical support of the existence of common cognitive structures. The cognitive theories are justified to the extent that they have received such empirical support and to the extent that essentially the same generic cognitive structures have been observed empirically using opposite formalisms in logic. This means that despite opposing views regarding the nature of our logic, cognitive theorists have discovered essentially the same underlying structure of human thinking and reasoning. It is also interesting to note that a Cognitive Task Analysis of the ORO activities (Matthews et al. 1999 a, b) has observed the instantiation of some of these cognitive structures even though the study did not use any theoretical framework to guide the research.

Our state of scientific knowledge at this point in the evolution of science represents one possibility among an infinite number of other possible accounts. It is entirely possible that a radically different theory may counter the present findings. This theory will nonetheless have to account for the empirical data that support generic cognitive structures in human beings.

In using logic, the review will not preclude other approaches to cognition nor will it apply formalisms of logic to all aspects of thinking. For example, we will discuss the use of language and mental imagery as instruments of our thinking. However, we will not enter into the lengthy scientific discussions among theorists as to whether logic structures language and mental imagery, or whether these processes structure logic. Moreover, there are also various new formalisms in the families of non-classical logic and in geometry that artificial intelligence use for software design but that are not presented in this review. We will not present all of these new formalisms here mainly because cognitive scientists have not yet formulated these logics as theories of human cognition. It goes without saying that these logics have not even been tested empirically to address the problem of human thinking. However, we truly believe that cognitive scientists, logicians, and computer scientists should engage in dialogues to bring new insights on human thinking and reasoning, and their relations to computer displays, namely tactical displays.

1.2 Review structure

The literature review has six sections:

- Naval tactical environment
- Content of mental representations
- Mental representations
- Role of belief biases and fallacies in reasoning
- Design issues
- Conclusions

1.2.1 Naval tactical environment

Section 2 pertains to the Naval Tactical Environment. This section comprises two parts. The first part characterizes the Combat Information Organization of the HCF. We will describe the Combat Information Organization in terms of its structural and functional components. The second part will pertain to the phases of naval operations. There are three main phases of naval operations: (1) mission preparation, (2) coming on watch, including watch transfer, and (3) on watch for surveillance, threat assessment, and threat response (Matthews et al., 1999a, b). The construction of mental representations is fundamental for effective situation awareness, reasoning, and decision making during each of these phases.

1.2.2 Content of mental representations

Mental representations are common to all human beings. They underline our ability to think, remember events, reason, and take decisions. Humans construct mental representations to represent some content, that is, information in memory. In section 3, we will determine the general properties and structure of the information that humans represent in memory.

1.2.3 Mental representations

Section 4 addresses relevant theories and research pertaining to the nature of Mental Representations. There are different levels of usage to the term mental representation. To account for these levels of usage, Section 4 consists of three parts.

The first part considers the concept of *symbolic representations*, that is, the use of symbolic tokens, such as words, to communicate information from the physical world (such as objects) as well as from long-term memory (such as concepts). Symbolic tokens communicate information but they do not represent the meaning of information.

The second part pertains to the *semantic representations,* the way in which humans organize and represent the meaning of information (such as sentences and pictures) after abstracting the details. Scientists have proposed different theoretical constructs to describe semantic representations. The two most recent and powerful constructs are: schemas, and mental models. We will specify three aspects of these semantic representations: (a) their structure, (b) their organization, and (c) their functions.

The third part describes the typology of semantic representations, that is, the fundamental categories and types of mental models that underlie human reasoning and decision making.

In addition to describing the above mental models, their potential application to the OR team's understanding of a tactical situation is discussed.

1.2.4 Role of belief biases and fallacies in reasoning

Mental representations include stereotyped beliefs that may have facilitative effects on these processes. However, stereotyped beliefs can also lead to biases and fallacies, that is, systematic errors in situation awareness, reasoning, or decision making. Section 5 addresses the issue of belief biases and fallacies in reasoning and the nature of belief biases from the point of view of two main theoretical models: the Selective Scrutiny model and the Misinterpreted Necessity model

1.2.5 Design issues

Section 6 addresses design issues and provides recommendations regarding the design of information displays in single-ship C2. These recommendations specify methods to support information management and the construction of mental models within a team perspective. The recommendations focus on display issues that should be solved in the HCF. There will be three parts to section 6:

- Support of physical mental models
- Support of conceptual mental models
- Support of shared mental models

1.2.6 Discussion, conclusions, and recommendations

Section 7 provides overall conclusions and identifies research issues based on the review.

2. Naval tactical environment

2.1 Combat Information Organization

The Combat Information Organization (CIO) of the OR has structural components and functional components.

2.1.1 Structure of the CIO

The CIO has two structural components: (a) a physical component consisting of an OR, and (b) a behavioral component consisting of a team of naval personnel (officers and non-commissioned members (NCMs)). The OR is a specialized compartment containing most of the CIO equipment displays and weapon controls of a ship.

The ship's Captain (CO) as the commanding officer is the head of the CIO. The CO is represented in the OR by the Combat Officer (CbtO). The CIO includes a 'Command row' which consists of the Combat Officer (CbtO), the Operations Room Officer (ORO), the Sensor Weapons Controller (SWC), the Assistant Sensor Weapons Controller (ASWC), and the ship's Aircraft Controller (SAC). The SAC, although considered a member of back row, does not actually sit in the back row.

The 'Command row' has the following role structure. The CbtO is responsible for supervising and co-ordinating the activities of the OR team. While on watch, the CbtO (or other ship ORO) is the CO's advisor on tactics; he/she is responsible for insuring speed and accuracy of response to counter any threat (Maritime Command, 1997). The CbtO is always an officer who has at least one sea tour as a weapons director, SAC, or navigator. The CbtO usually has spent one year as either the operations officer or weapons officer (junior ORO positions) before his appointment as CbtO. On watch, the SWC and the ASWC are both responsible to the on watch ORO. The SWC is responsible for the effective operation of the AAW and ASW sensors and weapons systems. The ASWC is responsible for the effective operation of ASW sensors and weapons. Both the SWC and ASWC have teams that collect and organize tactical stimuli for the SWC and ASWC use.

2.1.2 Functions of the CIO

According to CPF/TRUMP Establishment Review Missions and Functions, the CIO is responsible for conducting:

- Tactical warfare planning and direction
- Coordination of Maritime Ops to include disposition and reporting of forces; evasive steering; and HVU screening
- Fleet manoeuvring

- Individual ship navigation and blind pilotage
- Meteorological and oceanographic support
- Communications

Thus the CIO system has essentially three main functions:

- To provide input of tactical stimuli from computer displays
- To run software for processing the stimuli in terms of tactical picture
- To run software for compiling the output of stimuli in terms of the tactical picture for each warfare area, that is, a surface and subsurface picture, and an air picture

The OR team's primary functions are to:

- Manage tactical stimuli from all available sources
- Process the tactical stimuli
- Integrate the output of stimuli in terms of tactical pictures
- Interpret tactical picture in light of mission

2.1.2.1 *Managing tactical stimuli*

The OR team must manage vast amounts of stimuli (that is, data and information) coming from internal sources, that is, issued from own ship; and external sources, that is, coming from other ships, aircraft, and shore stations. Visual displays (sonar displays, radar displays, and electronic support measures) and verbal displays (oral and written information) present the stimuli. Oral stimuli are passed via radio circuits from shore stations, aircraft, and other ships. Written stimuli held on board include:

- Communications publications
- Tactical doctrine
- Operations orders
- Intelligence reports
- Charts for use during navigation
- Stateboards, that is, tabular display of stimuli that the OR team requires periodically

2.1.2.2 Processing tactical stimuli

The OR computers and the Command row are both involved in processing the tactical stimuli. The OR computers process the tactical stimuli through data collection, data fusion, and data integration. Integrated data about other ships, submarines, and aircraft is displayed for Command evaluation. The display of tactical stimuli in the local area is called a tactical picture. The Command row uses this tactical picture to help them visualize and evaluate military information.

The OR team members process the tactical stimuli using higher-level cognitive processes. In particular, the members have to encode, transform, and represent the stimuli in memory. Briefly, these processes consist of the following. Encoding consists in transforming incoming stimuli as information, that is, as data that has meaning and that humans can remember. Encoding involves selective attention a process whereby humans concentrate their attention on some aspects of tactical displays and not on others. The transformation of stimuli includes processes such as elaboration and organization. Elaboration consists in associating stimuli (such as unknown radar signs) to information that one possesses. Organization consists in grouping information according to various attributes and functions such as command structure and command function. Humans then store the processed information as a mental model or schema. This mental representation will then provide a basis for other high-level cognitive processes such as reasoning and decision making.

2.1.2.3 Presenting the tactical picture

Currently, two tactical pictures are maintained for the OR on the Command and Control System (CCS):

- The subsurface warfare area (movement of ships, submarines and underwater weapons)
- The surface and air warfare area (movement of ships, movement of aircraft, missiles and projectiles)

There are two scale displays to represent the warfare areas. One display presents the subsurface picture for the ASWC position, and the other display presents the surface and air pictures for the SWC position.

Picture compilation is a necessary step in presenting the tactical picture. Picture compilation of any type involves the following processes (Maritime Command, 1997):

- Detecting and reporting contacts and updating subsequent information.
- Displaying and tracking a contact's position either manually or automatically

- Categorizing and evaluating contacts for intelligence assessments.
- Amplifying contacts using identification arrays.

A basic goal of presenting the tactical picture is to increase the CIO's effectiveness in managing large amounts of stimuli so that the OR team can achieve fast and accurate response times. Another goal is to improve the display of the air, surface, and subsurface pictures in a way that best maps onto the mental representations of the OR team.

2.2 Phases of naval operations

During each phase of naval operations, the OR team constructs various forms of mental representations (mental models and schemas) to enable situation awareness, reasoning, and decision making. The presentation of this section, 2.2, is based on the Cognitive Task Analysis of the ORO activities (Matthews et al. 1999a, b).

2.2.1 Mission preparation

During mission preparation, commanders construct plans to deal with tactical events during the actual mission. During this phase, commanders have more time and less pressure to access information. These conditions allow them to consider multiple courses of action and select the best one. There are essentially four phases to the planning process. Commanders can short-circuit some of these phases depending on their level of experience in naval operations.

- Understand the tactical situation based on mission goals and higher command intent. The tactical situation includes knowledge of own and enemy strengths and weaknesses.
- Generate a set of alternative courses of actions based on a naval model(s) of tactics and C2. Commanders will consider the courses of action that the enemy can take given both own and enemy weaknesses and strengths. They will identify the most dangerous and the most likely enemy courses of action.
- In light of the mission's goals and enemy courses of action, evaluate and test the courses of actions through mental simulation or computer simulation. Generate a number of own courses of actions.
- Select the best course of action and create a plan for its implementation.
- Continually re-evaluate

There can be two different teams involved in mission preparation: shore-based planning teams (e.g., HQ staff) and planning teams afloat (e.g., task group, fleet staff). Both teams must communicate and co-ordinate their efforts in generating the pre-planned courses of action. Planning operations should also be flexible enough to consider multinational

operations. In these cases, Canadian planning staff may have to plan operations with NATO/Pacific Rim Naval Forces having potentially different theoretical models of C2.

During mission preparation (planning and rehearsal), the ship's Command row construct mental representations (mental models and schemas) that they will apply when they are on watch during the operations. When on watch, the Command row will seek to understand the current tactical situation with respect to the mental representations that they constructed during mission preparation. Understanding the tactical situation is likely to involve at least three cognitive processes. One process would consist of building an accurate mental representation of the current tactical situation. A second process would consist in identifying whether the pre-planned courses of action map onto the current tactical situation. The Command row may establish this mapping by identifying the similarities and differences between the current tactical situation and the pre-planned courses of action. A third cognitive process would consist of applying the appropriate pre-planned courses of action to the current tactical situation or updating their plans.

Thus, an essential aspect of mission preparation is to construct mental representations of pre-planned courses of action. These mental representations would provide an essential basis for accurate situation awareness and reasoning during the actual mission. This means that the OR team must properly represent the tactical situation before reasoning or taking decisions.

2.2.2 Coming on watch

When the OR team members come on watch, they have a set of goals that will direct their activities throughout the mission and prepare them to meet future threats (Matthews et al. 1999b, set out these goals). The OR team's preliminary goal is to update their awareness of the tactical situation. The watch transfer procedure affects all levels of situation awareness. Endsley (1995, 1997) characterizes situation awareness (SA) in terms of three levels of cognitive processing:

- Level 1 SA- Perception of the elements in the environment
- Level 2 SA- Comprehension of the current situation
- Level 3 SA- Projection of future situations.

At level 1 the OR team must perceive and manage large amounts of visual and verbal stimuli to become aware or update their knowledge of the tactical situation. The visual stimuli come from visual sighting of the physical environment and from visual displays. The verbal stimuli come from text-based messages and auditory-based messages.

At level 2, the OR team must update their understanding of the tactical situation and goals related to the mission. This understanding is required to develop an accurate mental representation of the tactical situation.

At level 3, the OR team projects future tactical situations. These projections consist in hypotheses concerning the evolution of tactical situations based on previous and current tactical events.

2.2.3 On watch

While on watch, the OR team have a set of goals for surveillance, threat assessment, and threat response (Matthews et al. 1999a, b). These goals involve all three levels of situation awareness. Figure 1 illustrates the processes involved when coming on watch and during watch. There are three main functions for on watch operations:

- Manage verbal and visual stimuli
- Construct mental representations
- Project future tactical events

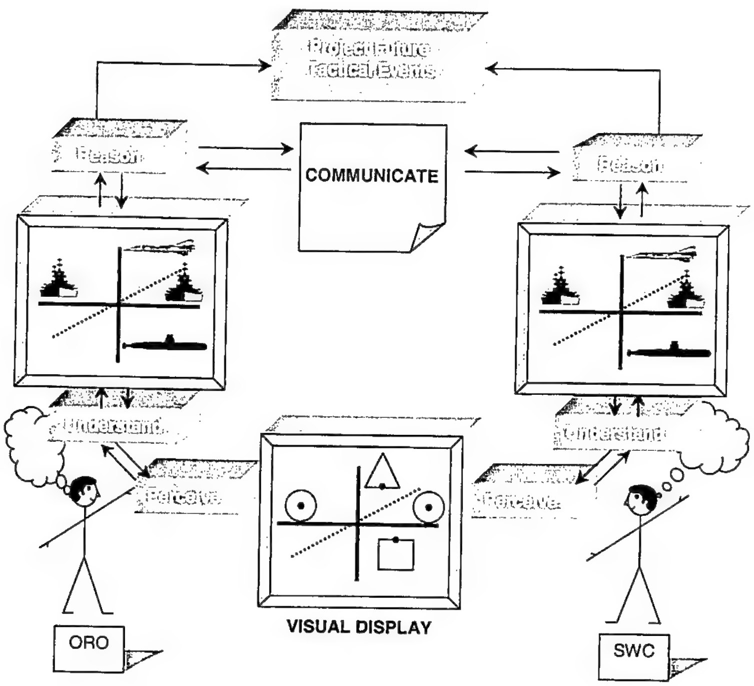

Figure 1. *The OR team members perceive military stimuli presented on visual display. Their comprehension of the external stimuli enables them to build a mental representation of the tactical situation. These mental representations will then enable naval personnel to reason about the tactical situation, that is, to make inferences concerning future tactical events. Communication of inferences will affect the way naval personnel represent and reason about the tactical situation.*

2.2.3.1 Manage visual and verbal stimuli

The OR team must manage vast amounts of stimuli from all sources coming to the OR. All sources of stimuli are potentially relevant to building and

maintaining situation awareness of the physical and operational environment. The OR team have various goals in managing stimuli. The front row, namely the Radar Tracker 1 (RT1) and Radar Tracker 2 (RT2), aim at transforming data into information. They achieve this by:

- Selecting relevant stimuli from visual and verbal displays
- Correlating and interpreting sensor data to determine the category of contacts

The front row disseminates the information to the SWC and ASWC in the Command row. The SWC and the ASWC transform this information into intelligence (assessed information) which they then pass on to the ORO. The ORO uses this intelligence for planning and updating their plan to counter future threats. Figure 2 illustrates these processes.

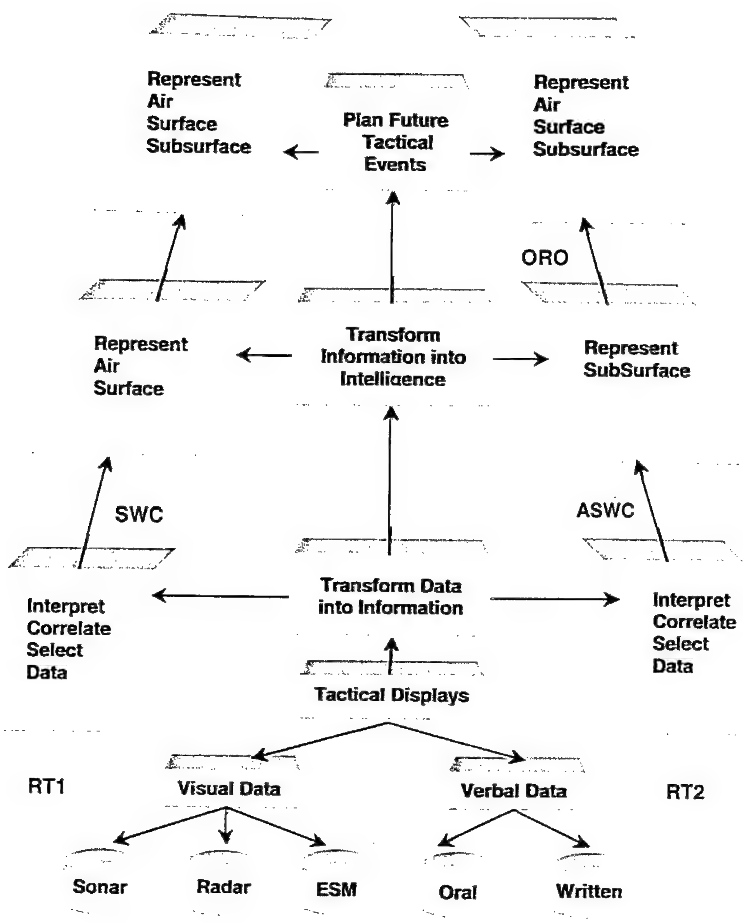

Figure 2. *C2 functions performed on watch. For example, the RT1 and RT2 in the OR transform visual and verbal data into information. RT1 and RT2 then transmit this information to the SWC and the ASWC. The SWC builds a mental representation of the air and surface areas; the ASWC builds a mental representation of the subsurface area. The SWC and the ASWC transform information relative to the different warfare areas into intelligence that they pass to the ORO. Using all available information, the CbtO and CO use intelligence to build an integrated representation of all warfare areas, and to plan future tactical events.*

2.2.3.2 Construct mental representations

As the OR team members maintain situation awareness of the tactical situation, they must build and maintain their own mental representation(s) of the tactical situation. Based on relevant theory and on a cognitive task analysis of the ORO activities (Matthews et al. 1999a, b), we make the hypothesis that the OR team members build three categories of mental models (see Figure 3). One category pertains to mental models of the physical environment. A second category

pertains to conceptual mental models of discourse (or communication) among own and enemy units. A third category pertains to shared mental models of team-mates' own mental models of team role structure and function. The typology of mental models (in Section 4.3) explains the nature of these mental models. Figure 3 illustrates the three categories of mental models and their use in representing and reasoning about different aspects of the environment.

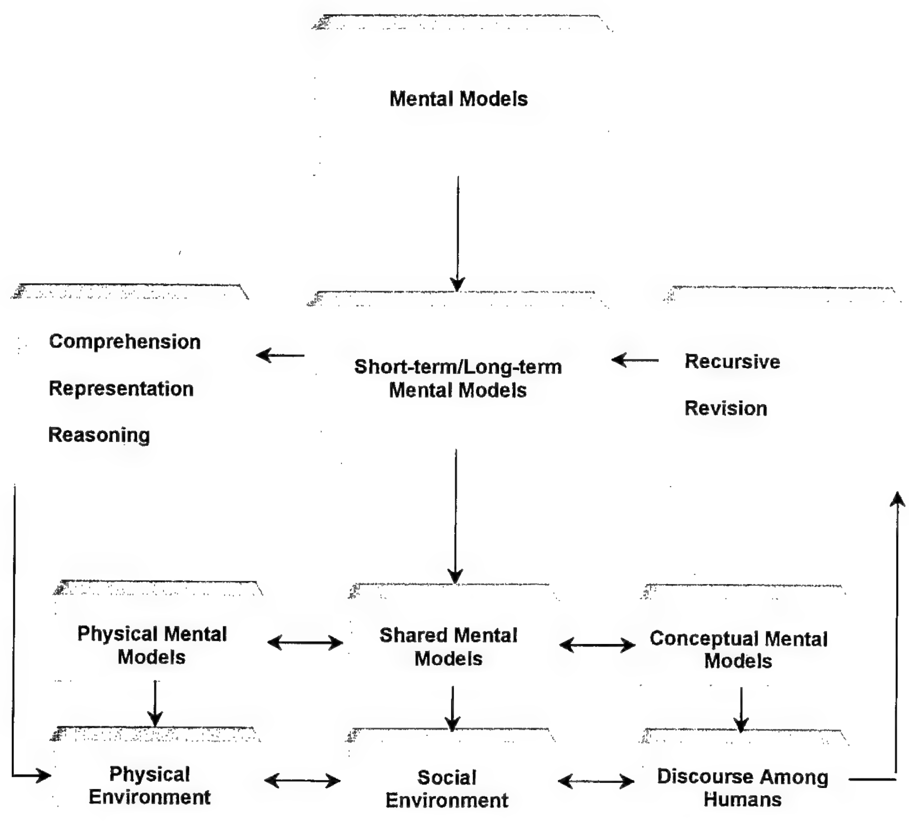

Figure 3. *The OR team members build three categories of mental models: physical mental models, shared mental models and conceptual mental models. These mental models would enable the OR team to comprehend, represent and reason about the different aspects of the environment. Changing aspects of the environment will lead the OR team to revise their mental model*

The cognitive task analysis of ORO activities (Matthews et al., 1999 a, b) suggests that the Command row build and update *physical mental models* of the pertinent air, surface, and/or subsurface warfare areas. The comprehension and visualization of each warfare area depends on the interpretation of auditory and visual stimuli from sonar and radar displays respectively.

The ASWC will construct a mental model of the *subsurface warfare area.* The SWC will construct a mental model of the surface and air warfare areas (see Figure 4). The ORO will build an integrated mental model comprising elements of each warfare area (see Figure 5).

Physical mental models comprise selected elements of the surface, subsurface, and air warfare area. For example, mental models of the surface picture may include all vessels within range of own ship or task group, the physical relations between ships (distance, velocity, and relative position), and the attributes of ships. The mental models may also include weather and oceanographic conditions, surface zones for navigation, and threat profiles of potential opposing and friendly forces. These elements can affect navigation and operations planning. In addition to constructing mental models of the different warfare areas, the OR team would form mental models of physical equipment (Matthews et al. 1999a, b) These mental models would be based on the dynamic properties of equipment structure and function. Mental models of equipment are required for routine maintenance and emergencies and own ship resources such as knowing which sensors are operable.

The OR team aims at building and maintaining *conceptual mental models* of the geographical, political, and military context. These mental models are based on verbal information such as tactical doctrine, operations orders, and intelligence reports (Matthews et al. 1999a, b). The conceptual mental models are also constructed from the past, current, and future tactical situations.

Finally, the OR team must build and maintain *shared mental models* of the team role structure and functions (Matthews et al., 1999a, b). These shared mental models would form the basis upon which the Command row co-ordinate and direct the activities of the naval personnel.

As they manage the OR naval personnel, the ORO, SWC and ASWC must also accomplish their own tasks. As a result, they face a problem of multiple tasking whereby they are required to balance the accomplishment of their own tasks with supervision tasks. This process requires shifting attention from different mental models, and planning time according to priorities and mission goals (Matthews et al., 1999a, b).

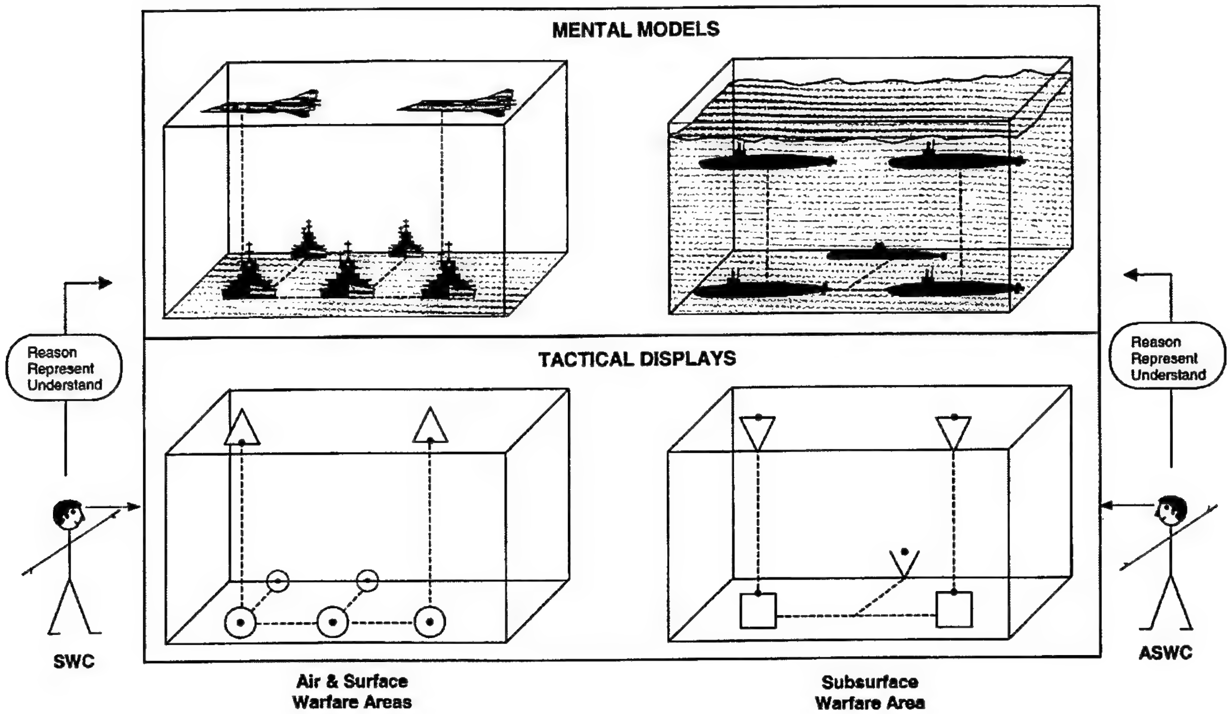

Figure 4. *The SWC will construct a mental model of the surface and air warfare areas. The ASWC will construct a mental model of the subsurface warfare area.*

MENTAL MODEL

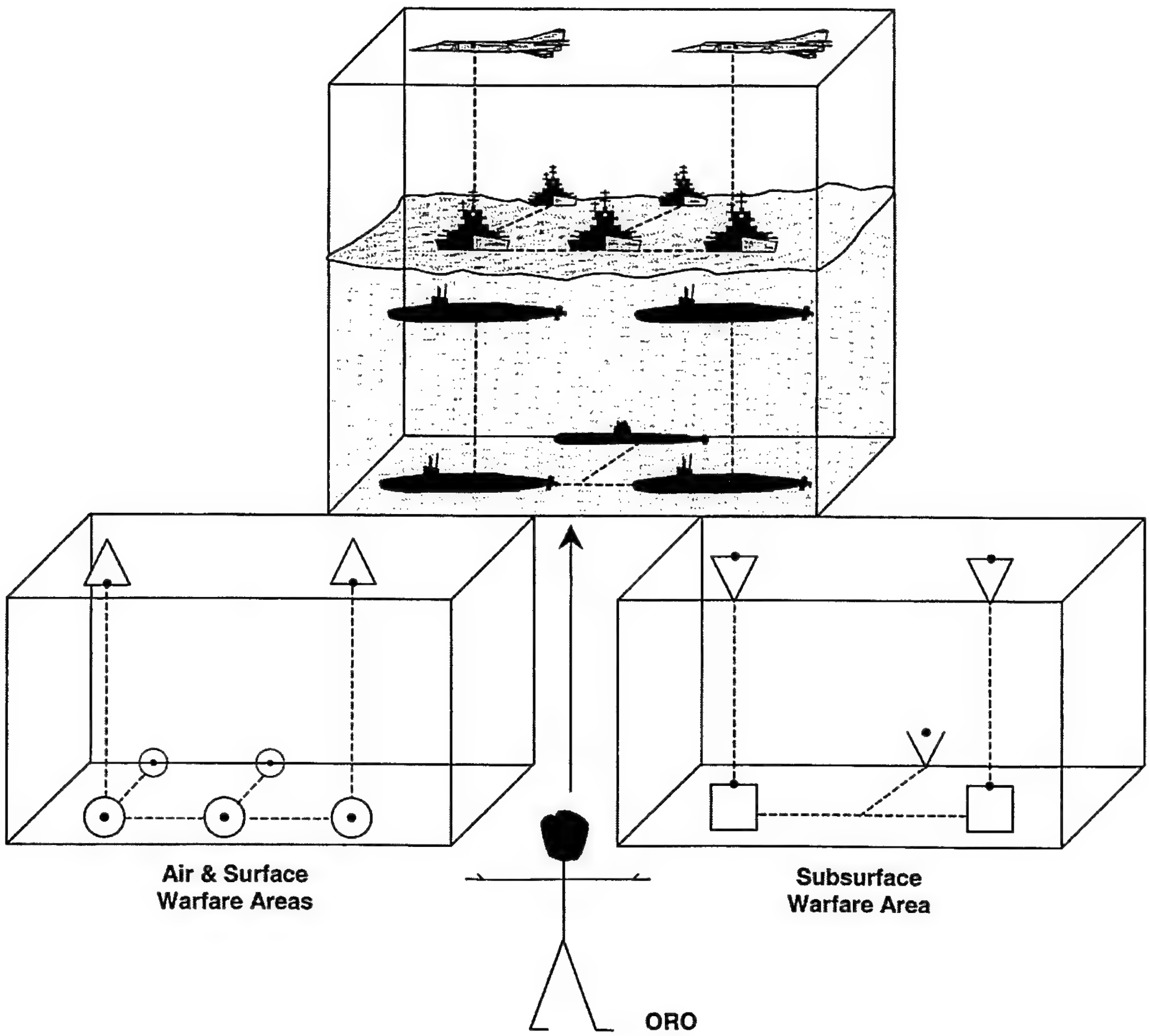

Figure 5. The ORO builds a big picture of the tactical situation, that is, a mental model comprising elements of each warfare area.

2.2.3.3 Project future tactical events

Having constructed mental models of the tactical situation, the Command row will project future tactical events. The Command row bases their projections of future tactical events on the threat assessment. Threat assessment starts with the OR's sensor operators who detect and correlate sensor data to determine the identity of military contacts.

The sensor operators send the information regarding category of contacts to the ASWC and SWC. In turn, the ASWC and SWC recommend courses of action to the ORO and CO regarding the tactical employment of weapons systems, ships, and aircraft. Based on threat assessment, the CbtO and CO make projections concerning future enemy actions and own courses of action. These projections will form the basis upon which to manoeuvre and engage targets in the future.

On watch threat assessment and threat response generally occur under time pressure and high stress. Because the Command row must respond quickly and accurately, they may often consider satisfactory courses of actions rather than an optimal one. To attain this goal, the Command row can use the pre-plans developed during mission preparation and/or develop new plans.

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3. Content of mental representations

Humans construct mental representations to represent content, that is, information in memory. Figure 6 presents a visual illustration of the relations between mental representations and content represented. The literature distinguishes two general types of content: physical information and semantic knowledge. The term physical information refers to information that is available to the human sense organs and that has meaning relative to an individual. Figure 6 illustrates levels of abstraction regarding physical information. One level pertains to concrete objects and events in the physical world. Another level pertains to structured objects and events in the physical world. A more abstract level pertains to structured objects and events presented in information displays. For example, radar displays present structured objects and events from the surface and air warfare areas.

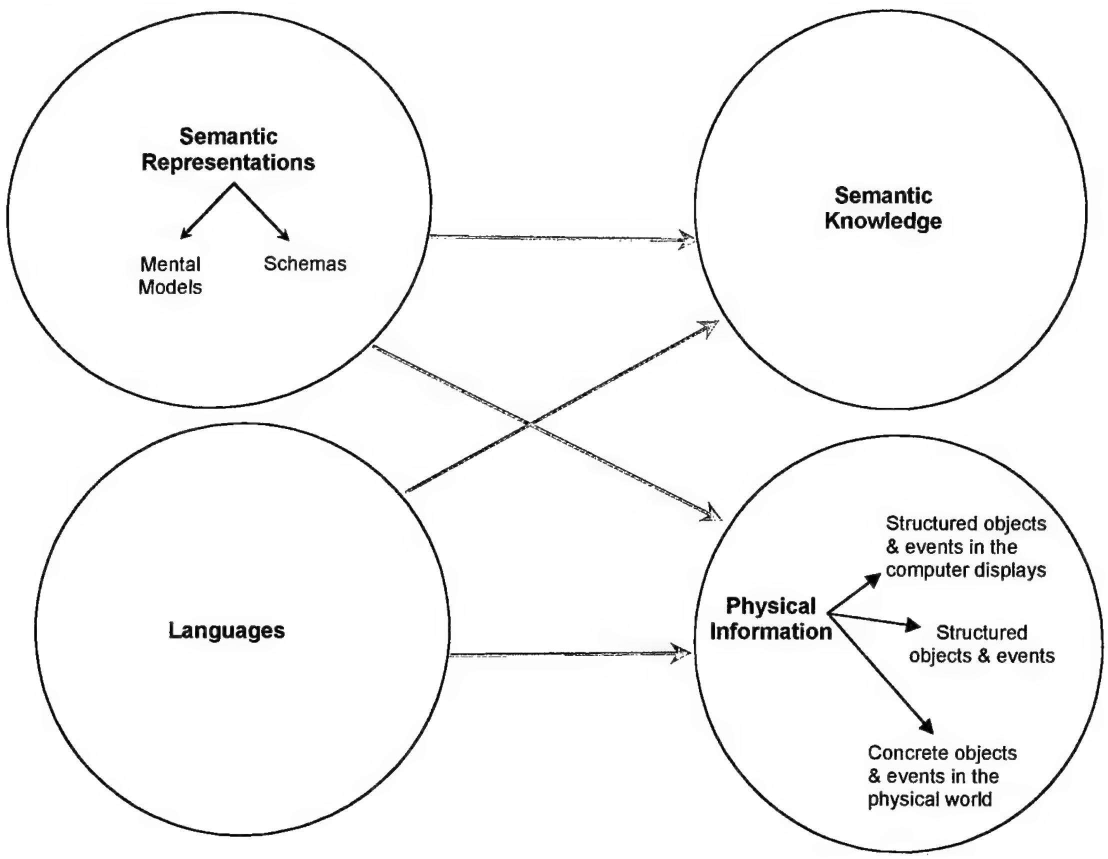

Figure 6. *There are two main distinctions to the term mental representation. The first pertains to the use of symbolic representations, that is the use of language as a system of signs and symbols. The second refers to semantic representations (which include mental models and schemas) that comprise the use of signs and symbols. Humans use symbolic representations and semantic representations to represent physical information and semantic knowledge.*

The term semantic knowledge pertains to information stored in memory. In a general sense, semantic knowledge consists of long-term knowledge of the physical world and language (Craik, 1943; Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991; Tulvin, 1972, 1983). In a more specific sense, semantic knowledge can refer to any entity, such as an object or concept that has meaning relative to an individual. The literature distinguishes two general types of entities: physical entities and conceptual entities. Physical entities include objects (such as ships), their attributes (such as size or shape), and their relations (such as relative position). Conceptual entities include concepts (such as military ship), their attributes (such as friendly or enemy ship), and their relations (such as defend or engage). Although conceptual entities can apply to the physical world, they do not necessarily have a basis in the physical world.

There are two kinds of attributes: defining attributes and characteristic attributes. Defining attributes are necessary to the meaning of an object or concept. For example, in order to be classified as a fighter aircraft, an object must have certain attributes common to all objects known as fighter aircraft. A set of necessary attributes defines an object (or concept) as a member of a type (such as F-14) or category (such as Fighter aircraft). All objects in the type or category share the defining attributes. In contrast, characteristic attributes are typical of an object (or concept) but they are not fundamental to the definition of an object (or concept). For example, we may associate certain characteristic attributes with fighter aircraft (such as shape) but the attribute cannot be a defining attribute of the object. Smith, Shoben, and Rips, (1974) argue that humans generally determine the meaning of an object or concept by the whole set of attributes, both defining and characteristic.

Cognitive scientists argue that physical and conceptual entities, which form the basis of semantic knowledge, are organized in memory as hierarchical structures (Anderson, 1991, 1995; Anderson & Bower, 1973; McDonald, Samuels, & Rispoli, 1996; Osherson, Smith, Wilkie, Lopez, & Shafir, 1990; Rosch, 1973, 1975, 1977; Quillian, 1968, 1969). As illustrated in Figure 7, a hierarchical structure of semantic knowledge can include objects (or concepts), types, categories, and supercategories. These represent increased levels of abstraction from most concrete (objects) to most abstract (supercategories).

There are four organizational dimensions that structure semantic knowledge in memory: classification, generalization, aggregation, and partition. Classification associates objects (e.g., the Halifax-class Frigate (HCF)) or concepts that have common attributes with a type (such as military ship), a category (such as ship), and a supercategory (such as platform). Generalization organizes semantic knowledge into hierarchies relating entities to types, types to categories, and categories to supercategories. Figure 7 illustrates a generalization hierarchy. The generalization hierarchy allows inheritance of the attributes and relations associated with a higher-level of the hierarchy to a lower-level one. For example, the attributes and relations associated with military ships generalize to the HCF. Aggregation relates an object to its components or parts. For instance, the HCF has components such as decks, accommodation spaces, a machinery space, and an Operations Room. As in the case of classification, aggregation can be applied recursively to the object's parts so that the hierarchy can represent the components of the components of an object. Partitions are generalization hierarchies applied to the component parts of an object. Partitions involve grouping the component parts of an object into a hierarchical organization.

Thus, objects (and their component parts), types, categories, and supercategories of entities form a hierarchical structure of semantic knowledge. Studies in cognitive psychology have provided evidence supporting the psychological reality of hierarchical semantic knowledge (Herrmann &

Harwood, 1980; Osherson et al., 1990; Rosch, 1975, 1977). In addition, the hierarchical structure supports "cognitive economy" because it allows inheritance of attributes and relations through the generalization hierarchy. For example, we know that all military ships have guns so this attribute is specified once within the type called military ships.

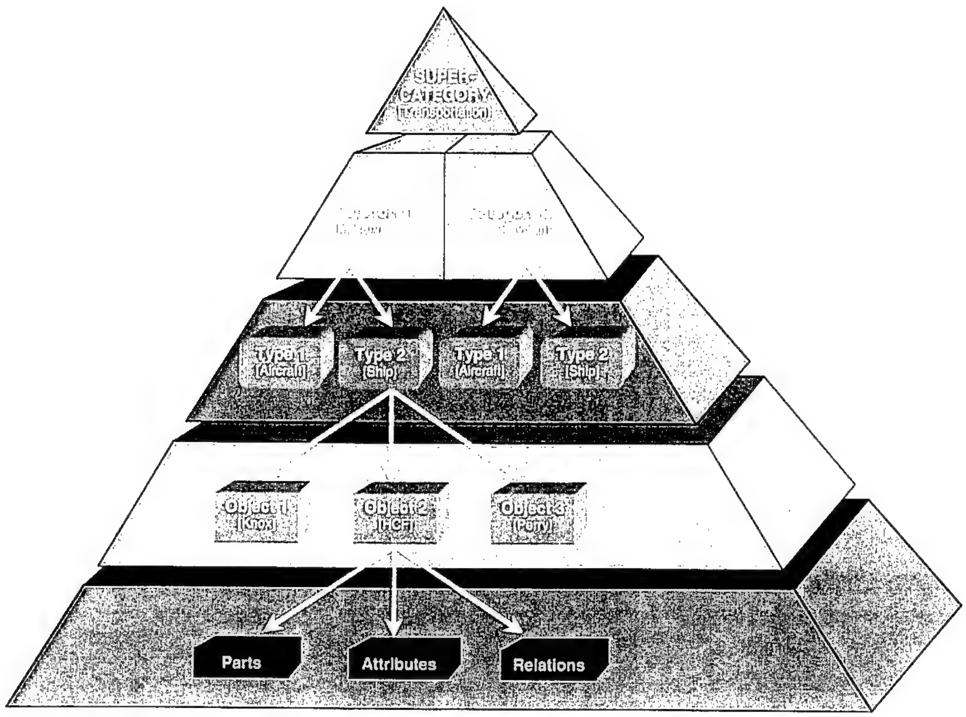

__Figure 7.__ A hierarchical structure comprises different levels of abstraction, from concrete objects to a supercategory. The arrows indicate that a lower- level of the hierarchy is embedded within a higher-level.

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4. Mental representations

There are two main theoretical views of the concept of mental representation: one pertains to the concept of Symbolic Representations and the other to the concept of Semantic Representations and their fundamental types.

4.1 Symbolic representations

Symbolic representations pertain to languages (natural or formal) that humans use to communicate information to other humans or to computers. Natural languages include spoken, written, and signed languages. Formal languages include technical languages used in different areas of human endeavors, such as in the military sciences and technologies. All languages (natural and formal) have a lexicon, that is, a basic vocabulary consisting of a set of symbolic tokens such as words and images (see Figure 8). The function of symbolic tokens is to allow humans to represent and communicate information in human interaction or in human-computer interaction (Kendon, 1996; McNeill, 1992; Newell, 1990; Paivio, 1971, 1986; Piaget & Inhelder, 1963).

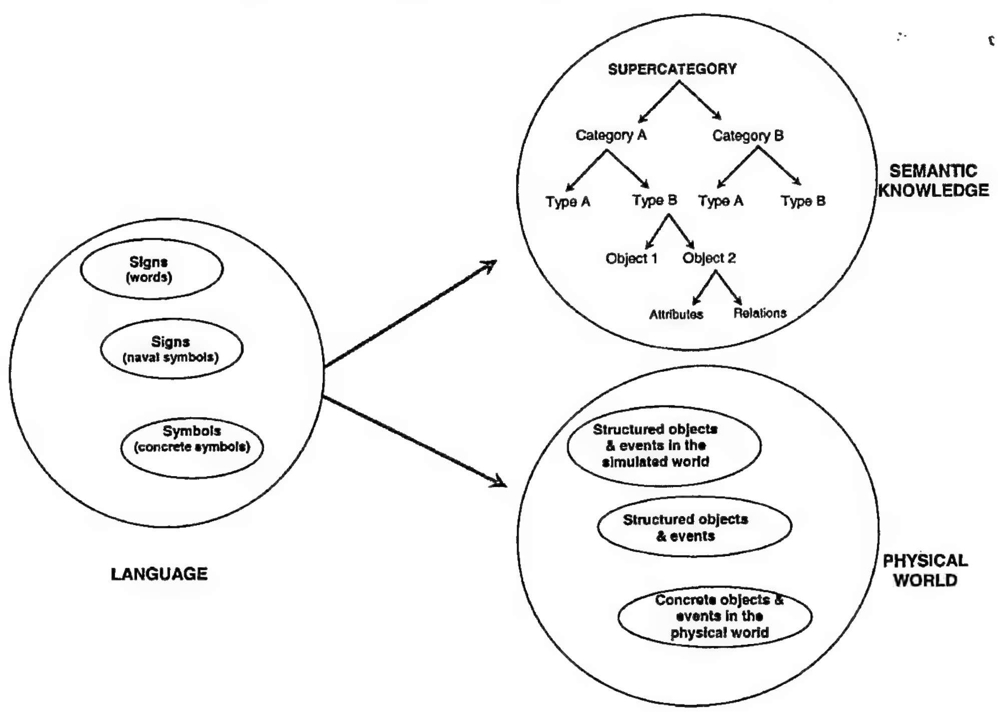


Figure 8. *Symbolic representations pertain to languages that humans use to communicate information stored in memory (semantic knowledge) as well as information from the physical world (objects and events).*

Psycholinguistic studies distinguish two types of symbolic tokens: symbols and signs (Ellis & Hunt, 1989; McNeill, 1992; Palmer, 1978; Piaget, 1983; Saussure, 1959). *Symbols* are symbolic tokens that are differentiated (separate) from their entity but they maintain similarity in form with them. Such is the case of pictures or map features. *Signs* are also differentiated from their entity but are relatively arbitrary. Such is the case of words, and the characters used for tracks on naval tactical displays. There are two general *modes* in which the OR team can perceive and communicate symbolic tokens depending on the human sense organ (or modality) involved. These include (1) vocal-acoustic tokens and (2) visual tokens. Humans can convey *vocal-acoustic tokens* vocally as spoken words or non-vocally as sonar signals or alarms. *Visual tokens* may take a graphical or non-graphical form. Visual-graphical tokens are those that are physically depicted on a visual display such as naval signs on radar displays or road symbols on maps, or drawings (Lee, 1999). Symbolic tokens that have a visual component with no physical presentation on a visual display are termed visual-non-graphical tokens. These include manual (hand) symbols (Boudreau & McCann, 2000; Kendon, 1996; McNeill, 1992), and visual and spatial imagery (Jeannerod, 1994; Kosslyn, 1980; Paivio, 1971, 1986; Piaget & Inhelder, 1963).

Figure 9 provides examples of symbols and signs arising from the two general sensory modalities. The symbolic tokens can refer virtually to any level of a hierarchical structure of semantic knowledge. Scientists argue that humans use signs and symbols of the different modalities to convey concrete entities (such as pictures or objects) and abstract entities (such as concepts or categories). However, humans prefer to use symbols to convey concrete entities and signs to represent abstract entities (Nelson, Reed, & McEvoy, 1977; Paivio, 1971, 1986; Palmer, 1978). Humans use symbols and signs to represent entities in schemas and mental models. Symbolic representations as well as semantic representations (schemas and mental models) represent content, that is, information from the physical world as well as information in memory (see Figure 8).

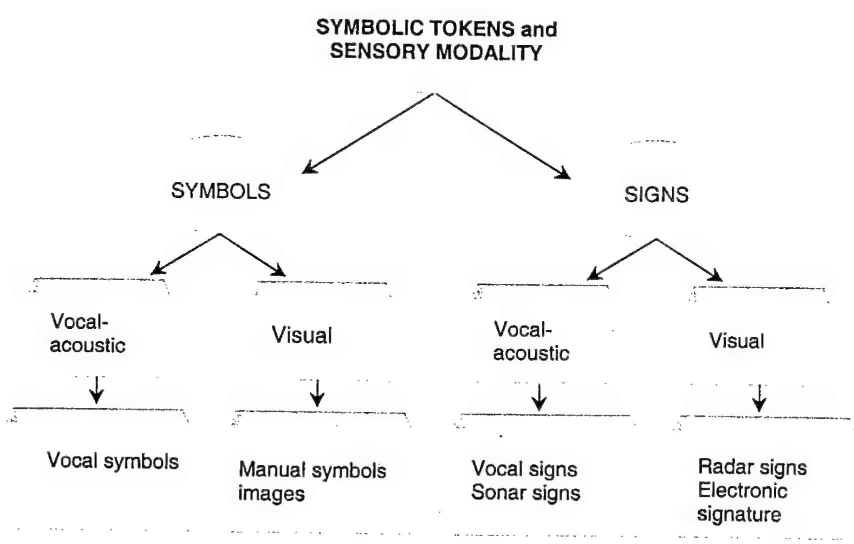


Figure 9. *Examples of symbolic tokens of the vocal-acoustic and visual modalities.*

4.2 Semantic representations

Cognitive scientists argue that semantic knowledge is organized in memory as hierarchical structures (Anderson, 1983, 1991; Anderson & Bower, 1973; Osherson et al., 1990; McDonald et al., 1996; Rosch, 1975, 1977; Quillian 1968, 1969). Models of semantic knowledge aim at describing this organization in a formal (theoretical) system. Formal systems are called *semantic representations* because they represent the meaning of physical pictures and physical sentences after humans have abstracted the details. The two most recent and powerful types of semantic representations are schemas that would represent information in long-term memory, and mental models that would represent information in short-term and long-term memory.

4.2.1 Schemas

The theoretical construct of schema has its roots in the cognitive theories of Piaget (1936, 1947, 1972, and 1975) and Bartlett (1932). The theories view schemas as generic knowledge structures that characterize each level of cognition. Thus, there are perceptual schemas (Neisser, 1967), sensory-motor schemas (such as eye-hand co-ordination) and representational schemas (concrete and abstract) (Piaget, 1936). Sensory-motor and perceptual schemas form the basis from which humans construct representational schemas. Cognitive scientists (Anderson, 1995; Norman & Rumelhart, 1975; Rumelhart, 1980) recognize schemas as "building blocks of cognition" (Rumelhart, op cit). Recent theories of cognition provide explanations for the structure, organization, and functions of schemas.

4.2.1.1 Structure

Schemas represent semantic knowledge in terms of generic attribute-feature structure, generalization hierarchy, partitions, and constraints (Anderson, 1995; Norman & Rumelhart, 1975; Rumelhart, 1980). Schemas represent semantic knowledge according to a *generic attribute-feature structure*. Generic attributes are common to members of a type or category. As illustrated in Table 1, attributes include materials, function, shape, and size. The HCF has the following set of attributes of military ships, and for each attribute, there are associated features.

Table 1. Example of a generic attribute-feature structure of a frigate.

	ATTRIBUTES			
	Isa (Is a)	***Material***	***Function***	***Shape and Size***
Features (examples)	Ship	Steel, brass, wood, wiring, plastic, glass	Float, move, fight	Rectilinear Tons (2,000 – 5,000)

The features are called default values, that is, they hold true unless explicitly contradicted. The features characterize a given object (or concept) such as the HCF. In contrast, attributes are more generic and can thus apply to a category of objects (or concepts). For example, the attributes of the HCF characterize our schema of ships and can thus apply to our concept of civilian ships. However, all of the features of the HCF may not be appropriate for civilian ships.

We can distinguish conceptual and perceptual attributes. Attributes can be essentially conceptual as in the case of the function of a ship, or they can be perceptual as in the case of shape or size. Schemas encode common attributes that are generally true about instances (that is, individual objects) whether these attributes are conceptual or perceptual.

Within a *generalization hierarchy* a special attribute, called an ISA attribute, points to a category (such as ship, that is, the attribute links the object (or concept) to a higher level of the hierarchy such as a category. For example, in Figure 7, the HCF is embedded within the type military ships, and the type military ship is embedded within the category military transportation. In the schema, the hierarchical links between the object (or concept), the type, the category, and the supercategory form a generalization hierarchy that represents the structure of semantic knowledge relevant to ships. Through the generalization hierarchy, the object (or concept) inherits attributes and features of the higher levels of the hierarchy. For example, the category military transportation allows us to infer by inheritance that the HCF has other attributes common to ships although the HCF schema does not specify all of these attributes.

A second type of hierarchy is called a *partition* (also referred to as part hierarchy). Parts of the HCF have their own schema definitions. For example, the HCF has an OR, decks, machinery space, and other parts. As for the schema of ships, these components have a generic attribute-feature structure, a generalization hierarchy, and partitions.

Schemas have *constraints* that enable humans to infer the category membership of instances within contexts. For example, the attribute of a ship in good condition is to be able to navigate on the sea surface. If it navigates and is under the surface, it is no longer a ship but a submarine. Constraints specify category membership in terms of typicality, that is, the extent to which objects have the typical attributes of the schema or match the prototype, that is, the best example of a schema. Earlier studies on category membership (e.g., Rosch, 1975, 1977) pertained to natural categories like birds or vegetables. Natural categories have a hierarchical structure that characterizes schemas. Typical attributes and/ or prototypes form the basis upon which humans judge the degree of category membership. For example, experimental evidence shows that pictures of birds are easier to recognize as birds when the pictures represent typical attributes, such as flying, which characterize the schema of birds.

Categories based on typical or characteristic attributes do not have fixed boundaries because the typical attributes are not defining attributes. Thus, an

object such as penguin can be a member of a category such as birds although it does not have the typical attributes or features of the category, such as flying. These objects are referred to as peripheral objects in that they do not have the typical attributes of the central (or typical) members of the category (McCloskey & Glucksberg, 1978). Peripheral objects are more difficult to judge than are central members of a category. Studies have shown that there is both lack of inter-subject consistency and intra-subject consistency regarding category boundaries (McCloskey & Glucksberg, 1978). Moreover, perceptual features and context affect the consistency of categorization judgements.

4.2.1.2 Organization

Schemas organize objects and concepts according to a hierarchical structure of semantic knowledge. Schemas are organized among themselves as hierarchical structures that integrate lower-level schemas into higher-level ones (Neisser, 1967; Rumelhart, 1980). The integration occurs in long-term memory to account for developing expertise.

Cognitive theories have proposed two main complementary views concerning the processes that underlie the organization of schemas, the Abstraction theories (Reed, 1972; Anderson, 1991) and the Instance theories (e.g., Smith, Shoben, & Rips, 1974). Abstraction theories argue that humans organize schemas by abstracting common attributes and features of instances, that is, of individual objects. The relations among the common attributes form a type of object, and the relations among types form a category. In identifying an object, humans then judge the similarity of the object's attributes and features relative to those of the type or category (Reed, 1972; Anderson, 1991). In contrast, Instance theories hold that humans remember instances rather than a generic set of attributes. The instances form the basis upon which humans organize the prototype (or best example) of a category. People then judge the similarity of the instances relative to the prototype.

Although the above theories invoke different accounts of the organization of schemas, they make essentially the same predictions. The theories argue that the more similar an object is relative to a type or category the easier it will be to identify. Moreover, connectionist models have modeled the Abstraction theories and the Instance theories (Anderson, 1995). Some connectionist models have shown that humans abstract common attributes (and features) that are present in instances without keeping a record of the instances. Other connectionist models have shown that humans keep a record of the instances and form a prototype from these instances. Thus, we can argue that common attributes and prototypes form the basis of the organization of schemas. We can also assume that the naval personnel organize schemas of military knowledge using common attributes and features and/or prototypes.

4.2.1.3 *Functions*

Schemas can account for a wide range of cognitive processes that are essential for the OR team. These cognitive processes include information sampling, recognition and categorization of observations, and inferences (Anderson, 1983; Brewer & Treyens, 1981; Cheng & Holyoak, 1985; McDonald, et al., 1996; Murphy & Ross, 1994).

4.2.1.3.1 *Information sampling*

In the naval context, information sampling consists of selecting relevant information from tactical displays in order to construct an accurate mental representation of a tactical situation. Information sampling is important for the OR team's situation awareness because the OR members must update their knowledge of the tactical environment as its various features change at different rates.

Control structures, which are sources of activation, direct information sampling for schemas. The process of activation occurs in two directions (see Figure 10), one is conceptually driven (top-down) and the other is a data driven (or bottom-up). In conceptually driven processing, a higher-level schema activates a sub-schema. The activation flows from higher-level schemas to lower-level ones based on expectations of the nature of information to look for. The activation of the sub-schema derives from higher-level expectations that a sub-schema will be able to account for some of the data or information. In data driven processing, stimuli that humans perceive from the environment activate a low-level schema. An activated low-level schema causes the activation of various higher-level schemas. For example, the activation of the HCF schema causes the activation of the military ship schema. The two processes of activation can occur concurrently or successively.

When on watch, the OR team will attend to and select information guided by the two processes of schema activation. Selective sampling of information will save time and effort in building situation awareness, and thus increase speed and accuracy of response to enemy courses of action. This function of schemas is critical for all phases of naval operations. However, selective sampling can result in biased perception and judgement, and thus in errors in decision making.

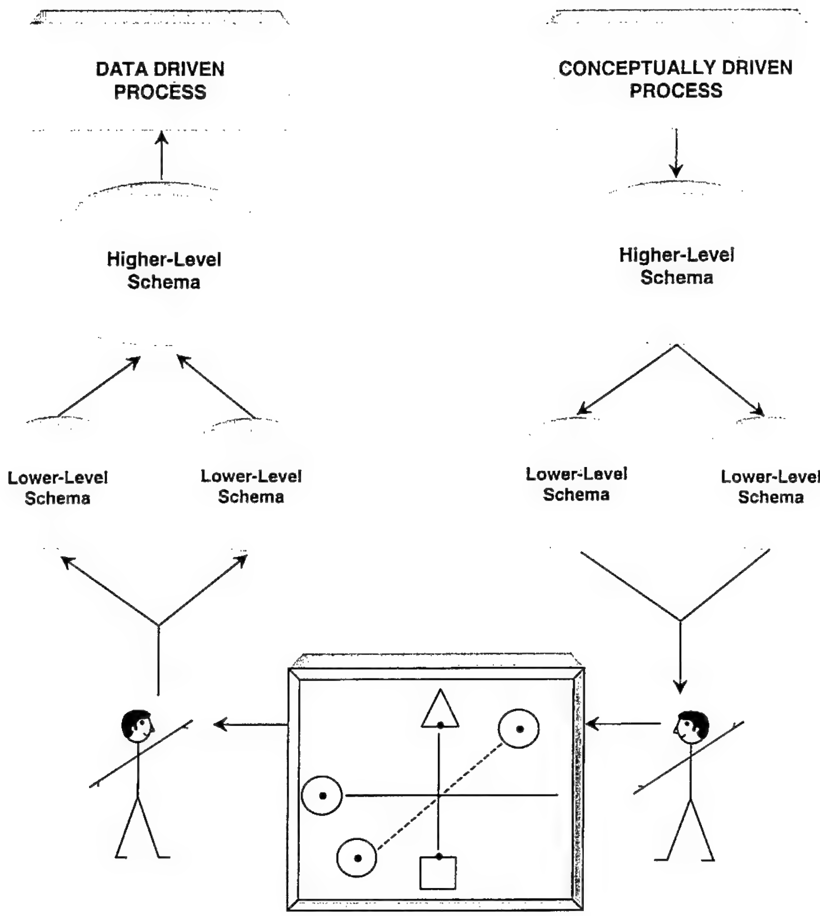


Figure 10. *Schemas direct information sampling according to two directions of processing: one is conceptually driven and the other is data driven. In conceptually driven processing, a higher-level schema activates a sub-schema. The activation flows from higher-level schemas to lower-level ones. In data driven processing, stimuli that humans perceive from the environment activate a lower-level schema. An activated lower-level schema causes the activation of various higher-level schemas.*

4.2.1.3.2 Recognition

Long-term memory schemas have an important role in categorizing perceived stimuli (data or information). This process of categorizing is part of level 2 of

SA and provides a basis for other processes such as making decisions. Schema-based categorization is essential for recognition-primed decision strategies. These decision strategies involve matching attributes (and features) of an entity (e.g., object or situation) to those of schemas, or matching an entity to the prototype of a category. For example, in studies of fire ground commanders, Klein (1989) found that experts match the critical attributes (and features) of a situation to those of schemas in order to determine an appropriate course of action from long-term memory. It may also be that experts take decisions by matching an individual situation to a prototypical situation. Klein also found that tactical commanders match the attributes (and features) of a situation to those of a category of pre-planned courses of actions in order to quickly understand a situation (Lipshitz & Shaul, 1997; Klein, 1997). It thus appears that schemas form a crucial basis for recognition-primed decision strategies.

Scripts, a type of schema, have also been proposed to portray actual prototypical situations (Minsky, 1975; Schank & Abelson, 1977). Schank & Abelson have proposed the construct of scripts as a type of schema (also called an event schemata: Mandler, 1984). Scripts characterise situations that involve a prototypical sequence of actions. A frequently sited example involves dining at a restaurant. A prototypical sequence of actions includes entering a dining area, ordering a menu, and leaving. Scripts have essentially the same structural properties as those of schemas (see section 4.2.1 on schemas). Scripts thus include a generic attribute-feature structure, generalisation hierarchies, and partitions. Schank and Abelson have tested the psychological reality of scripts. The authors have shown that the main sequence of actions in a typical situation characterizes people's conception of the situation. Scripts thus consist of prototypical sequences of actions that occur in standard temporal positions. Studies have shown that people place events in their usual order (e.g., ordering a menu before paying) even if the events are presented to them in an unusual order (e.g., paying before ordering). Humans thus appear to represent typical situations relative to a script that affects the encoding and recall of these typical situations.

4.2.1.3.3 Inferences

Schemas allow humans to make inferences (or conclusions) concerning the identity or category of objects (or concepts) they represent. These inferences can be probabilistic deductions or probabilistic inductions. *Probabilistic deductions* are deductions in which a conclusion regarding an entity is likely but not certain partly because humans derive the conclusion from uncertain information (visual or verbal) (Johnson-Laird, 1994 a, b; Murphy & Ross, 1994). For example, if we recognize an object, such as an aircraft, as a member of a category such as fighter aircraft, we can infer with certain degrees of certainty that it probably has the attributes associated with the category. These probabilistic deductions are based on the default values or features of the schema. The default values hold true unless explicitly contradicted. For example, given that all fighter aircraft have a set of attributes (shape, altitude, speed, and course) and that "X" is a fighter aircraft, we will deduce by default that it probably has the attributes of the fighter aircraft, unless we receive

additional conflicting information. In Artificial Intelligence, scientists (Bachman, Levesque, & Reiter, 1989) have proposed computer models of probabilistic deductions. However, there are very few studies, if any, on the processes by which humans make probabilistic deductions from schemas. This issue is critical given that the OR team members are required to make deductions from uncertain information, both visual and verbal.

Probabilistic inductions are likely generalizations that humans infer from a given set of observations (e.g., objects, attributes, and situations) (McDonald et al., 1996; Osherson et al., 1990; Sloman, 1993). For example, one can infer the possible identity of an object from a given set of attributes such as speed, signature, and altitude. The belief that we have that the conclusion is true, regarding the identity of an object, depends on the number and nature of attributes that support the conclusion. Conversely, the belief in the truth of a conclusion decreases as the attributes and features of the observations depart from the schema's typical attributes and features.

In conclusion, schemas can represent hierarchical structures of semantic knowledge. They enable selective information sampling, categorization, and inferences. Schemas also support our understanding of the relationships between categories having different attributes or prototypes (Anderson, 1991, 1995). However, schemas do no account for the human capacity to construct mental representations of physical events or discourse as they occur in real time or in the present. It is likely, given experimental evidence (see for example, Johnson-Laird & Byrne, 1991, 1993; Matthews et al., 1999a, b), that mental models would provide the essential basis for mental representations of actual events as well as past and future events.

4.2.2 Mental models

Scientists have followed two main directions of research to semantic representations related to mental models (see Figure 11). One direction, Johnson-Laird's Mental Models theory (Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991, 1993) and experimental research in cognitive research represents the main work on generic mental models (see Figure 11). A second direction, which reflects aspects of human factors research, has addressed empirically, content specific, or task specific, mental models and is thus related to expertise. Such human factors research pertains to the understanding of physical systems (Gentner & Stevens, 1983; Greeno, 1989; Kieras & Bovair, 1984; Norman, 1983; Rouse, Cannon-Bowers, & Salas, 1992); to shared mental models among team-mates (Cannon-Bowers, Salas, & Converse, 1993), to aspects of physical mental models (Matthews et al., 1999a, b); and to the potential application of mental models to the design of human-computer interfaces (Rouse & Morris, 1986; Wilson & Rutherford, 1989). While some research on content-specific mental models may represent the instantiation of generic mental models (Matthews et al., 1999a, b), the human factors direction of research does not necessarily, if at all, capture the common structure of mental models.

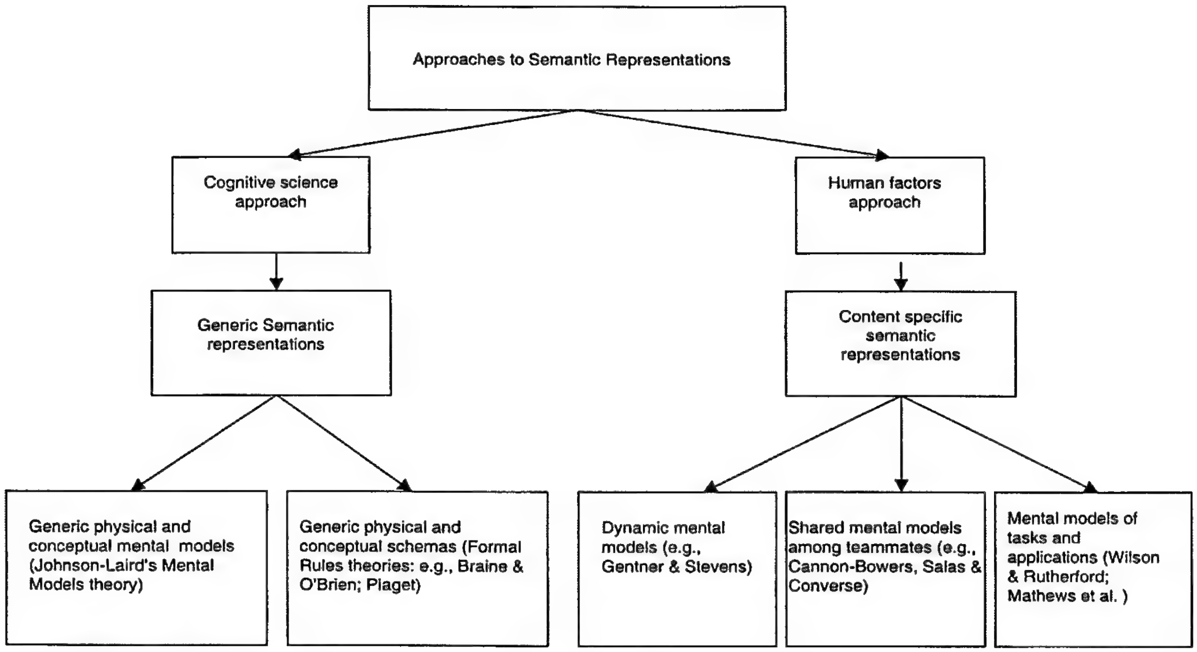


Figure 11. *Approaches to the concepts of semantic representations.*

Possibly because Wilson and Rutherford's (1989) analysis has focused on content specific cases, they assert that "the application of mental models will increase, rather than decrease, the total effort required to provide design recommendations". However, this problem should be solved if the generic structure of mental models can be used for design recommendations, since it should be common to adult thinking irrespective of expertise or working area.

The Mental Models theory (Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991, 1993) provides the most comprehensive account of mental models. The theory determines the fundamental mental models that would underlie human cognitive competence irrespective of formal training, task content, or level of expertise. One can compare these mental models to the basic anatomy of the human body. Despite differences in physical size or shape, all human beings have a common anatomical structure. Likewise, mental models are theoretically part of the fundamental "anatomy" or competence of the human mind (Evans, 1991; Evans, Newstead, & Byrne, 1993). Because of their fundamental nature, mental models should account for a wide range of cognitive processes that are essential for humans including the OR team. These processes include representing information (verbal or visual) as mental models and reasoning from them. Moreover, the numerous experiments of Johnson-Laird and his collaborators support the above contentions (see namely, Johnson-Laird & Byrne, 1991, 1993).

For the above reasons, the following sections will mainly represent the Mental Models theory's conception of the structure, organization, and functions of mental models (Johnson-Laird, 1983, 1994a, b; Johnson-Laird & Byrne, 1991, 1993).

4.2.2.1 Structure

Mental models have a structure that maps onto the relations among entities as they are perceived or conceived (see Figures 4 and 5). Johnson-Laird and Byrne distinguish various structural properties of mental models (Johnson-Laird, 1983, 1994a, b; Johnson-Laird & Byrne, 1991, 1993). The structural properties reviewed in this section are relevant for the OR team and for the design of information displays.

A mental model consists of individual symbolic tokens (such as images of ships or aircraft) that represent entities, their attributes (such as type of ship), and their relations (such as relative position or distance). Figure 12 illustrates a simple mental model of spatial relations among military aircraft. Each symbolic token represents an aircraft. The attributes of the symbolic tokens represent the attributes of the aircraft, and the relationships among the symbolic tokens represent the relationships among the entities. For example, a mental model of the sentences:

"The Mig is directly above the Bear", and "the F-14 is directly below the Bear", will have the spatial structure illustrated in Figure 12.

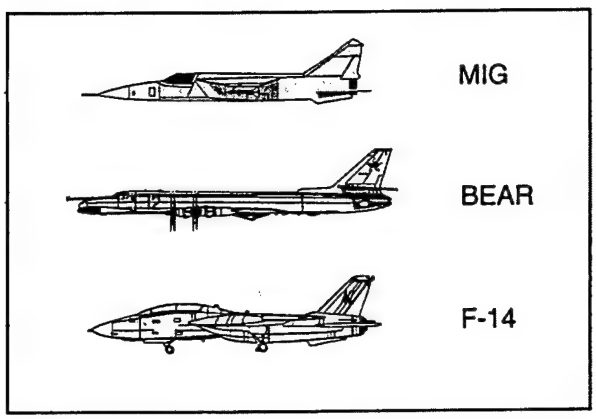


Figure 12. A mental model represents entities such as three military aircraft, their attributes such as type, and their relationships such as relative distance and position. (We provide examples for the pure purpose of illustration.).

Mental models will represent specific attributes and relationships to the extent that the sentences provide that information explicitly.

Thus, a mental model of sentences such as:

1. "The Mig is directly behind the Bear",

2. "The F-14 is directly in front of the Bear",

or a corresponding diagram such as:

"F-14 Bear Mig " (Where a person views the diagram from the front of the F-14.)

will have the spatial structure illustrated in Figure 13. Mental models would have the same structure irrespective of the mode (visual or verbal) in which one displays relationships among entities (Boudreau & Pigeau, 2001). However, mental models should be easier to construct from diagrams than from sentences because mental models are similar to the structure of diagrams. Experiments on formal reasoning support this assertion for spatial mental models (Boudreau & Pigeau, 2001) and for conceptual mental models (Barwise & Etchemendy, 1992; Bauer & Johnson-Laird, 1993).

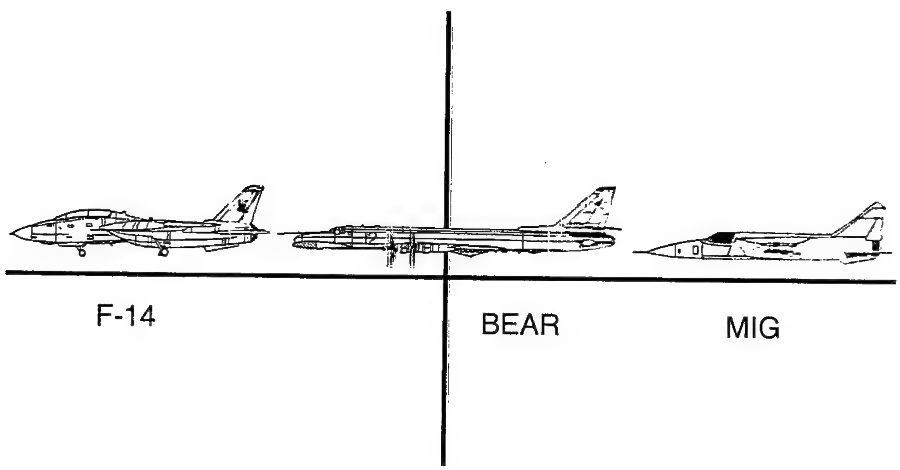


Figure 13. *The same mental model represents sentences and corresponding diagrams. Humans can imagine co-ordinate axes to help specify the relative position of the entities.*

A mental model represents alternative situations. This property is relevant is various situations, when humans deal with uncertainty (Johnson-Laird & Shafir, 1993). For example, the following sentences: (a) "the Bear may engage the F-14", or (b) "the Mig may engage the F-14", yield a mental model representing two alternative courses of action (see Figure 14).

An important aspect of mental models is that they enable humans to represent and reason about alternative hypotheses or situations that occur when events are uncertain.

This property should play a major role for the OR team because members must deal with tactical situations that are possible rather than certain. For example, during threat assessment, the command row will identify alternative hypotheses that appear reasonable, as illustrated in Figure 14. While projecting future courses of action, the OR team will identify and represent sets of alternative courses of action that the enemy may take relative to own courses of action. Figure 15 illustrates a mental model of a set of alternative courses of action.

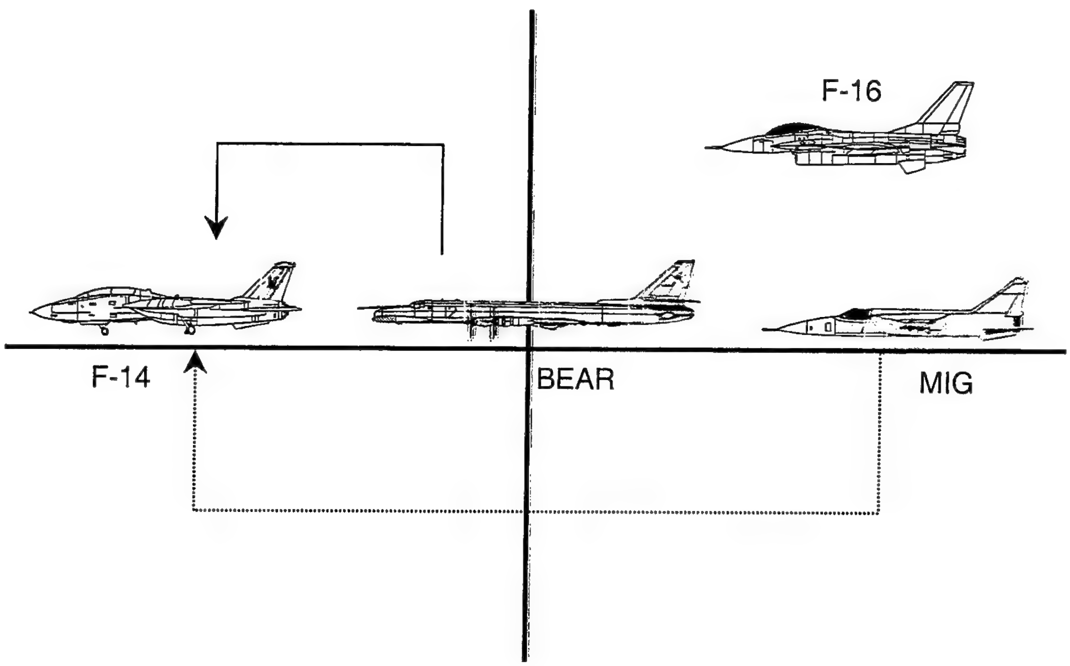


Figure 14. *Example of a mental model of alternative courses of action. The arrows represent the possible navigation paths of the Bear and the Mig: (a) the Bear may engage the F-14, or (b) the Mig may engage the F-14.*

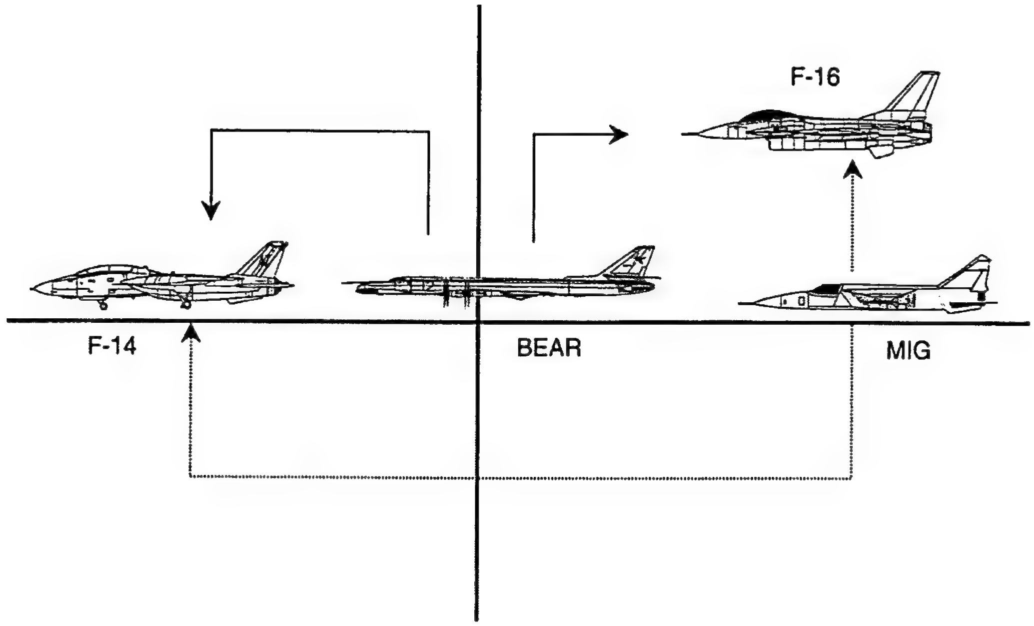


Figure 15. *A mental model can represent a set of alternative courses of action. The arrows represent at least four courses of action that the enemy aircraft (Bear and Mig) can take relative to own aircraft (F-14 and F-16). For example, either the Bear may engage the F-14 or the F-16, or either the Mig may engage the F-16 or the F-14.*

A mental model represents alternative situations either implicitly, to reduce the load on working memory (Johnson-Laird, 1983, 1994a, b), or explicitly, for immediate access for reasoning or decision making as a specific model.

Implicit mental models constitute generic mental models. For example, one can represent the enemy aircraft's' possible courses of action as a generic mental model that contains implicitly all possible navigation paths and their relations relative to own courses of action. In Figure 16, the mental model represents four courses of actions but it contains implicitly a set of nine possible ones. One could maintain alternative courses of actions generically and implicitly in memory until some of the courses of actions need to be fleshed out completely.

Mental models have a hierarchical structure in the sense that lower-level mental models (such as specific mental models) can be embedded within higher-level ones (such as generic mental models). Humans store generic mental models in long-term memory while they construct specific mental models in short-term memory from generic ones.

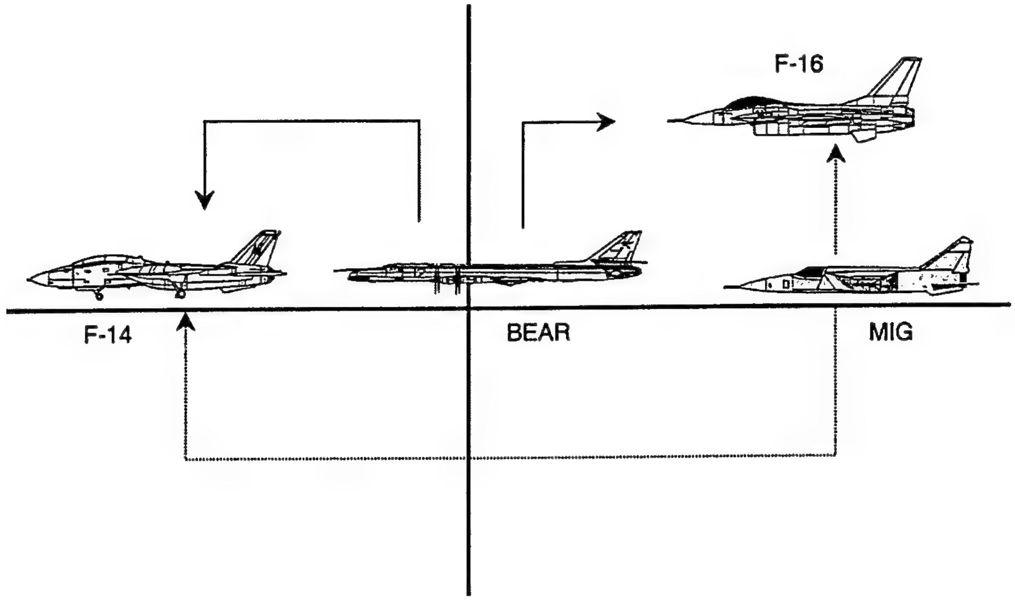


Figure 16. Example of a generic mental model of a set of alternative courses of action. The mental model represents four courses of action explicitly. By combining all courses of action, the mental model yields nine courses of action. The Bear may engage the F-14, the F-16, or both. The Mig may engage the F-16, the F-14, or both. The Bear or the Mig may engage the F-16, the F-14, or both.

4.2.2.2 Organization

The organization of mental models is based on the comprehension of physical events (such as diagrams), discourse (such as sentences), their integration, and recursive revision. These are ongoing processes for the OR team.

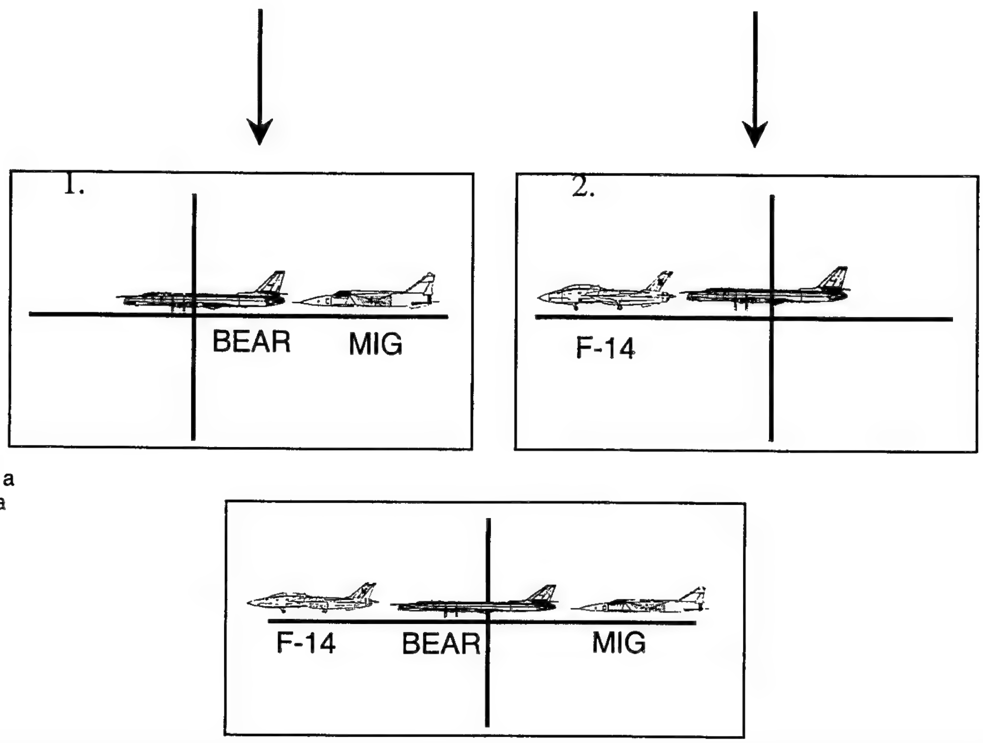
4.2.2.2.1 Comprehension of sentences and diagrams

Humans construct a mental model based on the comprehension of physical events (such as diagrams) or discourse (such as spoken sentences) among humans. The comprehension of discourse occurs in three main stages. During the first stage of comprehension, humans represent sentences such as those illustrated in Table 2. During the second stage, they construct a diagram of each sentence based on any relevant semantic knowledge. Humans would access semantic knowledge through schemas or mental models (Johnson-Laird, 1983; 1994a, b). During the third stage of comprehension, humans integrate the diagrams into a mental model. Table 2 illustrates the three main stages underlying the comprehension of sentences.

Table 2. Example of the three main stages (A, B, and C) underlying the comprehension of sentences.

COMPREHENSION OF SENTENCES

A. Represent sentences 1 and 2	1. The Mig is directly behind the Bear	2. The F-14 is directly in front of the Bear
B. Convert sentences 1 and 2 into corresponding diagrams		
C. Integrate diagrams 1 and 2 into a mental model using the "Bear" as a common entity.		

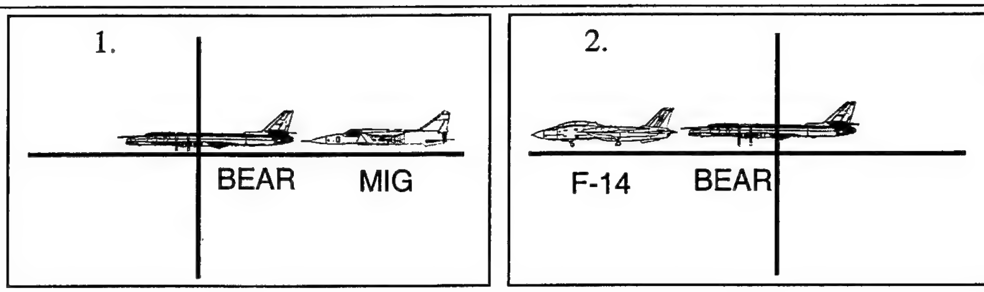


In the case of diagrams, humans bypass the mental representation of sentences and construct the mental model directly from the diagrams (Boudreau & Pigeau, 2001). The construction of mental models from diagrams also takes less time and is easier than from sentences because it involves two stages rather than three stages (see Table 3). The main difficulty in organizing mental models from sentences and diagrams arises from the fact that diagrams or sentences must be held in working memory while diagrams or sentences from other sources are combined with them (Baddeley, 1986; Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991, 1993).

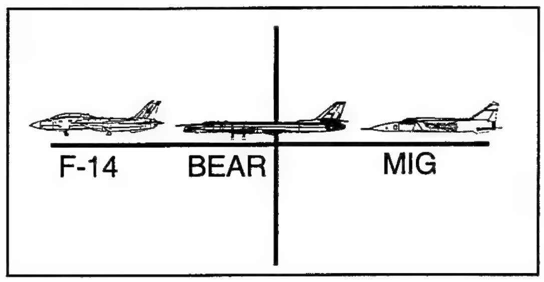
Table 3. Example of the two main stages underlying the comprehension of diagrams.

COMPREHENSION OF DIAGRAMS

A. Represent diagrams 1 and 2



B. Integrate diagrams 1 and 2 into a mental model



4.2.2.2.2 *Integration*

The SWC, ASWC and ORO must build integrated mental model(s) of the different warfare areas. If this is the case (Matthews et al., 1999a, b), then what is the nature of integration and what is the necessary factor for this process to occur?

The Mental Models theory (Johnson-Laird, 1983) defines integration as the possibility of constructing a single mental model. Integration depends essentially on referential continuity, that is, on the presence of a common entity among sentences or diagrams. There is referential continuity among sentences when each successive sentence has a common entity being referred to implicitly or explicitly. For example, the following two sentences have the entity Bear as a common entity:

1. The Mig is directly behind the Bear
2. The F-14 is directly in front of the Bear.

Likewise, there is referential continuity among diagrams when they refer to a common entity. For example, in Figure 17, the two diagrams have the entity Bear as a common entity. Humans will use the entity "Bear" common to the two diagrams to integrate these diagrams into a mental model (see Figure 18) (Boudreau & Pigeau, 2001).

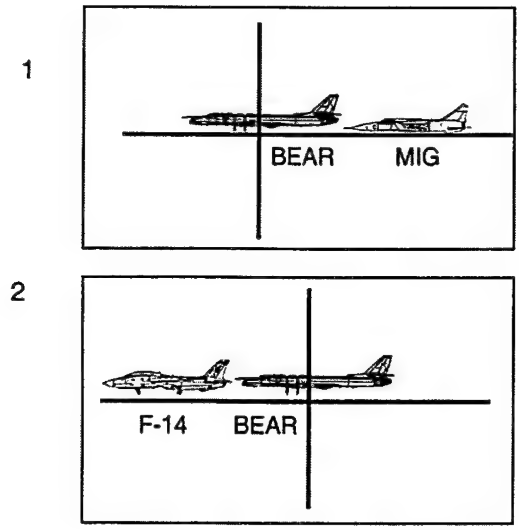


Figure 17. Example of two diagrams having a common entity (Bear). Diagram 1 corresponds to the sentence "The Mig is directly behind the Bear". Diagram 2 corresponds to the sentence "The F-14 is directly in front of the Bear". The above examples are simple ones. The Command row must construct mental models from complex sets of entities presented on different tactical displays.

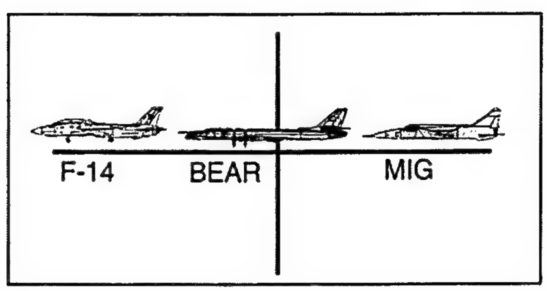


***Figure 18.** A mental model constructed from the integration of the two diagrams illustrated in Figure 17.*

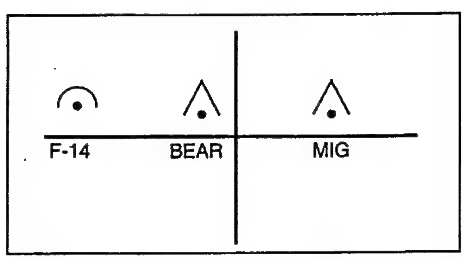
Referential continuity is the only condition that enables the construction of an integrated mental model. When sentences (or diagrams) have no entity in common, humans must construct independent mental models of the sentences or the diagrams (Boudreau, Pigeau, & McCann, 2000; Ehrlrich & Johnson-Laird, 1982). Maintaining multiple mental models in working memory is much harder than a single mental model as they systematically increase the load on working memory (Boudreau et al., 2000; Ehrlrich & Johnson-Laird, 1982; Mani & Johnson-Laird, 1982). The crucial factor for integration is thus the presence of a common entity between successive sentences or diagrams.

Johnson-Laird (1983) argues that the plausibility of sentences or diagrams will help construct integrated mental models. Plausibility depends on the interpretation of actual events relative to semantic knowledge (Miller & Johnson-Laird, 1976). However, plausibility is not a necessary or sufficient condition because if it occurs without referential continuity, integration becomes impractical (Johnson-Laird, 1983). Thus, referential continuity is a necessary condition for the construction of an integrated mental model.

4.2.2.2.3 *Recursive updating of mental models*

Given the uncertainty of tactical situations, will humans construct multiple mental models of discourse and physical events? The Mental Models theory (Johnson-Laird, 1983, 1994a b) argues that a single mental model would represent the meaning of discourse, and physical events, despite the fact that assertions and physical events are always consistent with more than one mental model. Humans need only a single mental model because they can revise their mental model recursively in light of the evolving discourse and physical events. Consequently, if subsequent assertions are inconsistent with a current mental model, humans will revise the mental model to accommodate the new assertions or physical events. Such recursive updating would be based on non-monotomic logics which are part of the families of non-classical logics. Figure 19 illustrates two consecutive displays of a changing tactical situation. Figure 20 illustrates the two consecutive stages in building a mental model of the tactical situation displayed in Figure 19. Despite the critical importance of updating mental models, the scope of effort has been in creating computer models of such processes rather than investigating how humans revise mental models.

19a.



19b.

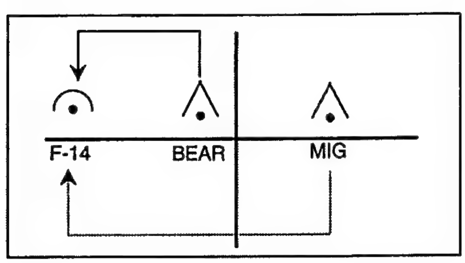


Figure 19. *Example of two consecutive displays of a tactical situation.*

20a.

20b.

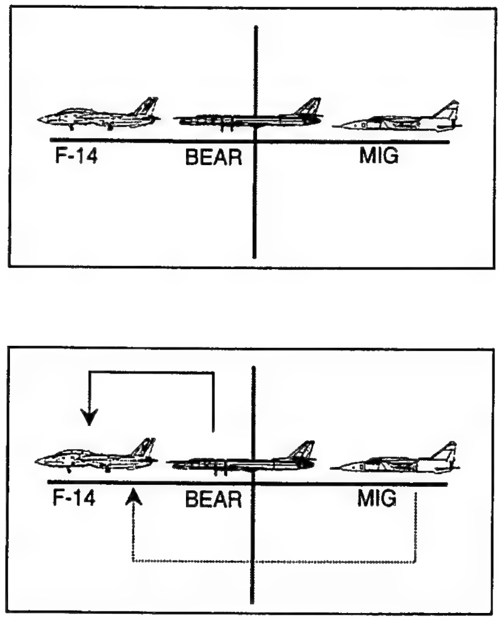


Figure 20. *Figures 20a and 20b illustrate two consecutive aspects of a mental model. In figure 20a, the mental model represents the tactical situation displayed in Figure 19a. In figure 20b, the mental model represents information regarding the potential navigation paths (arrows) of the same aircraft of figure 19b. Given the enemy's navigation paths, the OR team may predict that there are possible intentions of engagement from the Mig and the Bear.*

In conclusion, humans construct mental models of assertions and physical events based on their meaning. Mental models have recursive revision procedures that update them based on the evolving situation, whether based on discourse or on physical events. These revision procedures maintain both local and global coherence within a mental model (Albrecht & O'Brien, 1993: Radvansky, Spieler, & Zacks, 1991). Recursive revisions of mental models are essential for the OR team members because they must continuously maintain situation awareness and reason about the evolving tactical situation.

4.2.2.3 Functions

Mental models can provide the fundamental representation and mechanism for reasoning deductively, inductively, or probabilistically (Johnson-Laird, 1983, 1994 a, b; Johnson-Laird & Byrne, 1991, 1993). These processes occur at each phase of naval operations.

4.2.2.3.1 Representing information

As we have seen, a specific mental model represents specific entities, their attributes, and their relationships. A generic mental model represents implicitly

a set of possible alternatives that humans generate to account for an uncertain situation. The Mental Models theory (Johnson-Laird 1983; Johnson-Laird & Byrne, 1991, 1993) argues that the process of structuring information into a mental model occurs in two main stages: comprehension and description. A third stage, validation, is proper to reasoning.

In *Comprehension,* humans would first construct a mental model of sentences or diagrams based on their meaning and any relevant semantic knowledge to represent entities and their relations as they are perceived or conceived.

In *Description,* humans would then formulate a tentative conclusion from the mental model without resorting to orthodox (formal) rules of inference (see for example, Braine & O'Brien, 1991; Piaget, 1972; Rips, 1990), or even content-specific rules of inference (Cheng & Holyoak, 1985). In some cases, humans cannot draw a conclusion unless they flesh out an implicit mental model explicitly.

4.2.2.3.2 Reasoning

Johnson-Laird and Byrne (1991, 1993) have investigated the psychological reality of mental models as a fundamental basis for all the main forms of reasoning, that is, deductive, inductive, and probabilistic reasoning. Reasoning consists in validating a tentative conclusion (an inference or a decision) made from a mental model against alternative mental models that may falsify the conclusion. If there are no alternative mental models, the conclusion is deemed valid. If it is uncertain whether the conclusion is true in all alternative mental models, then humans can draw the conclusion in a tentative way that is, as a probability (Johnson-Laird, 1994a).

Each type of mental model provides the basis for a reasoning process, or a set of related reasoning processes. Spatial models underlie spatial reasoning; temporal models underlie temporal reasoning; hypothetical models underlie hypothetical reasoning. Rouse and his collaborators (Rouse et al., 1992) have identified three main functions of mental models that apply in complex C2 systems. Mental models enable (1) descriptions of system structure (what the system looks like) and functions (how it works); (2) explanations of the system's functions; and (3) predictions of future system states and functions. It appears likely that the three functions involve different forms of deductive reasoning. For example, the description function of mental models involves spatial reasoning, that is, reasoning about spatial relations such as locations among entities. The explanation function of mental models involves causal reasoning, that is, reasoning about the factors that cause an event. The prediction function of mental models requires hypothetical reasoning, that is, reasoning about hypotheses concerning future events. Finally, the three functions of mental models involve probabilistic reasoning, that is, reasoning about situations that are likely but not certain.

4.2.3 Relations between mental models and schemas

Mental models and schemas have various points in common both in terms of their organization and functions (Brewer, 1987). The main organizational properties and functions of schemas and mental models are compared in Tables 4 and 5. This comparison illustrates some of the strengths of each theoretical construct as semantic representations.

Table 4. Comparison of the main organizational properties o mental models and schemas.

ORGANIZATION	MENTAL MODELS	SCHEMAS
Hierarchical structure	+	+
Integration	+	+
Recursive updating	+	?

Note. In the case of a "+ ", theorists have provided a theoretical account of the property. In the case of a "?", theorists have not yet specifically accounted for the property.

Table 5. Comparison of the main functions of mental models and schemas

FUNCTIONS		MENTAL MODELS	SCHEMAS
Comprehension			
	Physical environment	+	+
	Social environment	+	+
	Discourse among humans	+	+
Representation			
	Short-term memory	++	+
	Long-term memory	+	++
Reasoning			
	Deductive	++	+
	Inductive	++	+
	Probabilistic	++	+

Note. In the case of a "+", cognitive scientists have accounted for the function related to mental models or schemas. In the case of a "++", cognitive scientists have provided for mental models (or schemas) a more comprehensive description and explanation of the function than for schemas (or mental models).

4.2.2.4 Organization

Schemas and mental models have a hierarchical structure. There are generic schemas that can be instantiated as specific schemas (Dutke, 1996; Rumelhart, 1980). The Mental Models theory (Johnson-Laird, 1983, 1994a, b) also recognizes the importance of generic schemas in constructing specific mental models. There are generic mental models that represent human cognitive competence (Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991, 1993). Humans would then use these generic mental models to construct specific mental models of a situation. Schemas are important because they represent semantic knowledge from which humans partly construct mental models (Brewer, 1987; Johnson-laird, 1983). Semantic knowledge (or long-term information) provides remote information from the specific mental model in order to account for an observed situation. This remote information is stored in schemas. In turn, humans would require mental models to represent information in real time (Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991, 1993). These relationships between mental models and schemas are mostly theoretical as there are very few studies that have addressed these issues (see Dutke, 1996).

4.2.2.5 Functions

Humans use mental models and schemas to understand information that they perceive from the physical environment, the social environment, and discourse. Mental models and schemas represent information in short-term memory and in long-term memory. However, the focus of research on mental models has been on the representation of information in short-term memory while the focus of research on schemas has been on the representation of information in long-term memory. Moreover, schemas do no account for the human capacity to construct mental representations of discourse or physical events as they occur in real time; mental models provide the essential basis for such mental representations (Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991, 1993).

The Mental Models theory (Johnson-Laird & Byrne, 1991, 1993) has provided a comprehensive accounted of the main types of reasoning: deductive, inductive, and probabilistic. However, scientists must still provide a theoretical account of the processes by which humans make inferences from schemas. Orthodox theories in logic (Braine, 1978; Braine & O'Brien, 1991; Hagert, 1985; Hagert & Hansson, 1983, 1984; Piaget, 1972; Rips, 1983, 1990) have proposed such accounts. However, their view has been the object of much controversy (Johnson-Laird & Byrne, 1991, 1993). Thus, while the concept of schema is supported by experimental evidence, the use of formal rules for reasoning has been challenged.

4.3 Typology of fundamental mental models and applicability in naval operations

Fundamental mental models are theoretically common to all adults irrespective of formal training, whether in science and technology, or professional expertise (Evans, Newstead, & Byrne, 1993). These semantic representations thus apply to novices and experts. These mental models may also underlie naval operations. The Mental Models theory provides most of the relevant research regarding the semantic representations that are part of human competence. As illustrated in Figure 21, orthodox theories in logic, such as Formal Rules theorists (Braine & O'Brien, 1991; Hagert, 1985, Hagert & Hansson, 1983, 1984; Rips, 1983; Piaget, 1972), have shown through empirical evidence, that there are generic schemas for physical knowledge (space, time, movement, causality) and for conceptual knowledge (e.g., hypothetical, propositional, categorical). However, Formal Rules theories have been the subject of systematic controversy in cognitive science (Roberts, 1993; Johnson-Laird & Byrne, 1991, 1993; Evans, 1991). Since recent Schema theories (Anderson, 1995; Norman & Rumelhart, 1975; Rumelhart, 1980) have not proposed any alternative account, then this review will focus on mental models and on three categories:

- Physical mental models
- Conceptual mental models
- Shared mental models

It is highly probable, given empirical evidence (see namely, Johnson-Laird & Byrne, 1991, 1993) that these mental models enable humans to represent and reason about aspects of the environment. Physical mental models would enable humans to represent and reason about aspects of the physical environment, that is, space, time, movement, and causality. Conceptual mental models would enable humans to represent and reason about aspects of discourse among humans. The category of conceptual mental models subsumes six types of mental models: (1) hypothetical, (2) propositional, (3) categorical, (4) relational, (5) inductive, and (6) analogical. Shared mental models would allow humans to represent and reason about the social environment. Shared mental models include knowledge of team role structure, functions, and the tasks that the team have in common, such as the tactical situation. Figure 22 illustrates the categories of mental models and their role in representing and reasoning about each aspect of the environment). Figure 23 represents the various categories and types of mental models (and schemas). The concept of schema remains empirically valid despite the fact that the related reasoning process is controversial.

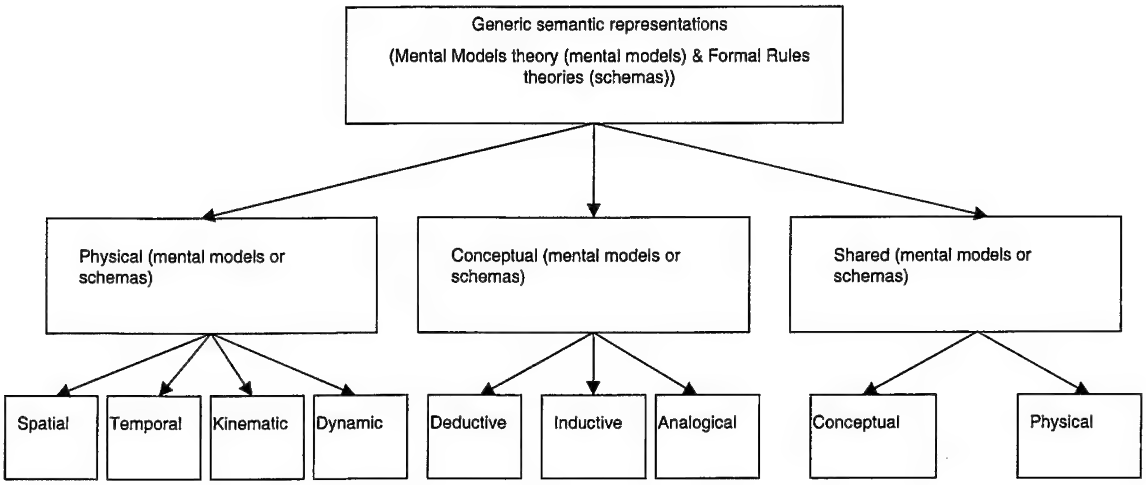


Figure 21. *The Mental Models theory and Formal Rules theories have obtained experimental evidence supporting the existence of generic semantic representations. The Mental Models theory has identified mental models, while the Formal Rules theories have identified schemas. The Formal Rules theories discovered empirical evidence supporting the existence of physical schemas and conceptual schemas. The Mental Models theory has obtained empirical evidence supporting the existence of physical mental models and conceptual mental models. Hypothetically, physical and conceptual (mental models and schemas) would be shared among members of a team.*

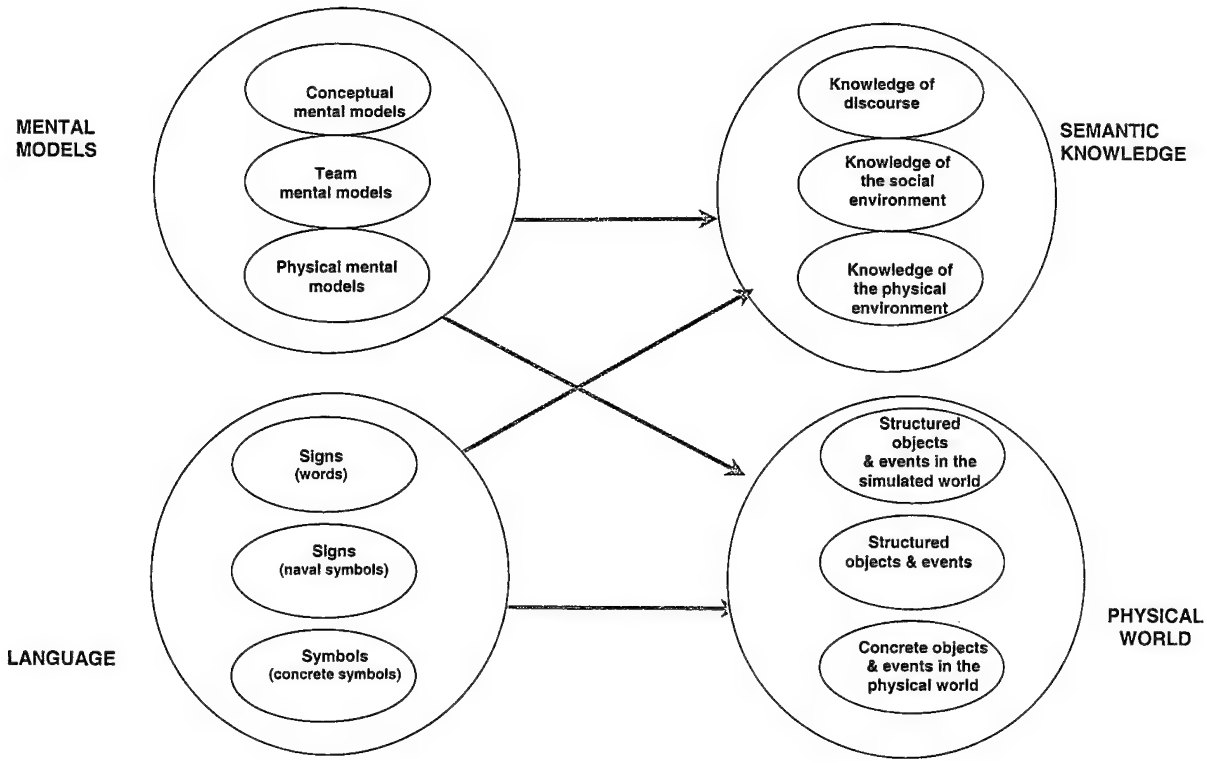


Figure 22. *Humans use mental models and language to represent semantic knowledge and physical information. Humans construct three categories of mental models: physical, shared, and conceptual mental models. These represent knowledge of the physical environment, the social environment, and discourse respectively.*

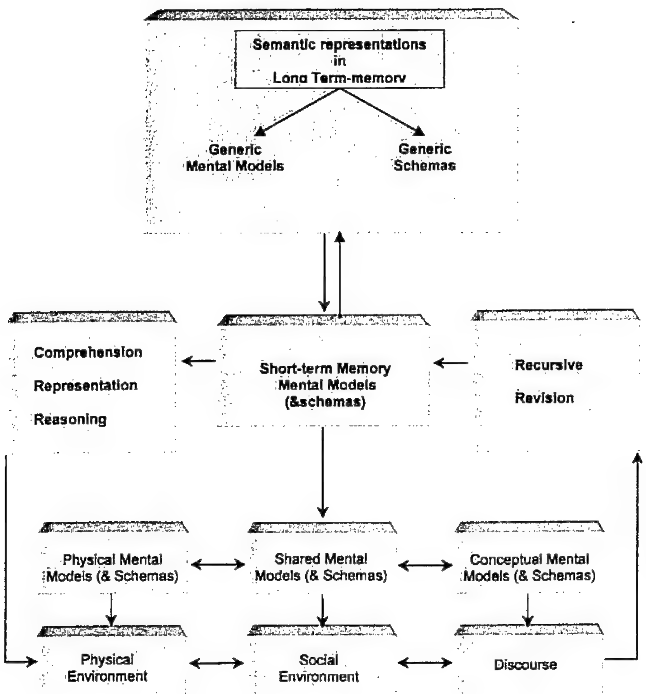


Figure 23. *The OR members build three categories of mental models (& schemas). These mental models enable the OR team to comprehend, represent and reason about the different aspects of the environment. Changing aspects of the environment will lead the OR team to revise their mental model of the environment.*

4.3.1 Physical mental models

Physical mental models apply to our understanding of some aspects of the physical world, that is, to space, time, motion, and causality. They represent physical objects, their attributes, and relations. It is highly probable that physical mental models are essential for the OR team members because they must build mental representations of the surface, sub-surface, and/ or air warfare areas (Matthews et al., 1999a, b). Each warfare area involves spatial, temporal, kinematic, and dynamic components. The category of physical mental models subsumes five types of mental models: (1) spatial, (2) temporal, (3) kinematic, (4) dynamic, (5) image, (see Figure 24).

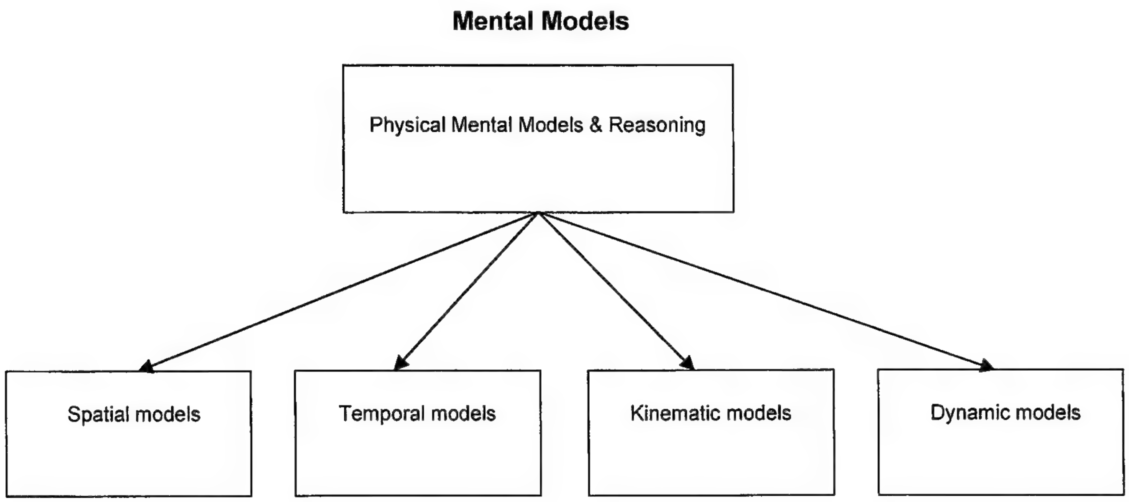


Figure 24. *Physical mental models include spatial, temporal, kinematic, and dynamic mental models.*

The terminology and distinctions between various types of physical mental models is consistent with the terminology that cognitive scientists and human factors scientists have used in their studies of human cognition. However, cognitive scientists have applied the concept of dynamic models in a very broad way that does not correspond to the use of the term in physics. If the concept of dynamic model were made consistent with the terminology in physics, the term dynamic would be restricted to the relationships between the concepts of force, momentum, and mass. Recent theories in human cognition have not yet investigated the concept of dynamics in its physical sense. However, the physical concept of dynamics may have been studied by Formal Rules theorists such as Jean Piaget. Moreover, while in physics, time is an integral part of kinematics, the distinction of temporal models is consistent with temporal logics and the fact that there are temporal models in human cognition (for example, see Bryne, Culhane, & Tasso, 1995).

4.3.1.1 Spatial models

Spatial models are an essential aspect of the OR team's mental representations because each warfare area is essentially spatial. As illustrated in Figure 25, a spatial model represents spatial relations among entities within a three-dimensional space. The Mental Models theory (Johnson-Laird, 1983; Byrne & Johnson-Laird, 1989) argues that mental models represent entities, their attributes, and their relationships. Thus, a spatial model should represent military entities, their attributes, and their spatial relations such as Euclidean relations, projective relations, and topological relations (see Figure 26). Cognitive studies have shown that spatial models reproduce Euclidean relations, such as dimensions (Boudreau & Pigeau, 2001; Byrne & Johnson-Laird, 1989; Mani and Johnson-Laird, 1982), and spatial relations, such as orientation and direction (Boudreau, et al. 2000; Boudreau & Pigeau, 2001).

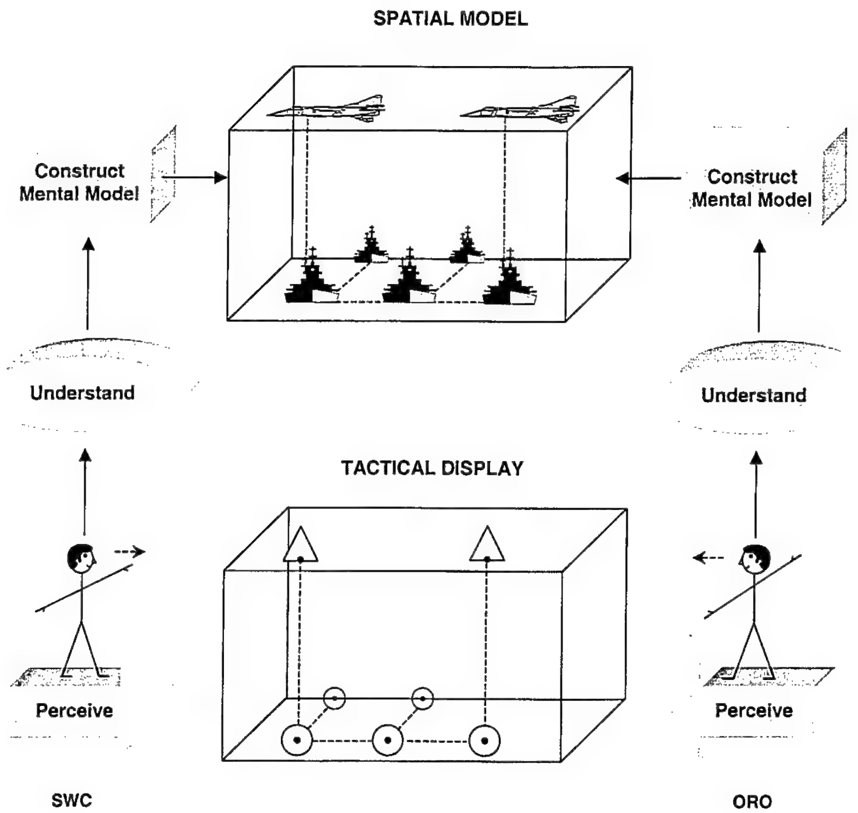


Figure 25. *The command row perceive tactical symbols from tactical displays. Their understanding of the tactical situation provides a basis from which to construct a spatial model of the tactical situation. The spatial model represents the three-dimensional spatial relations among the tactical symbols.*

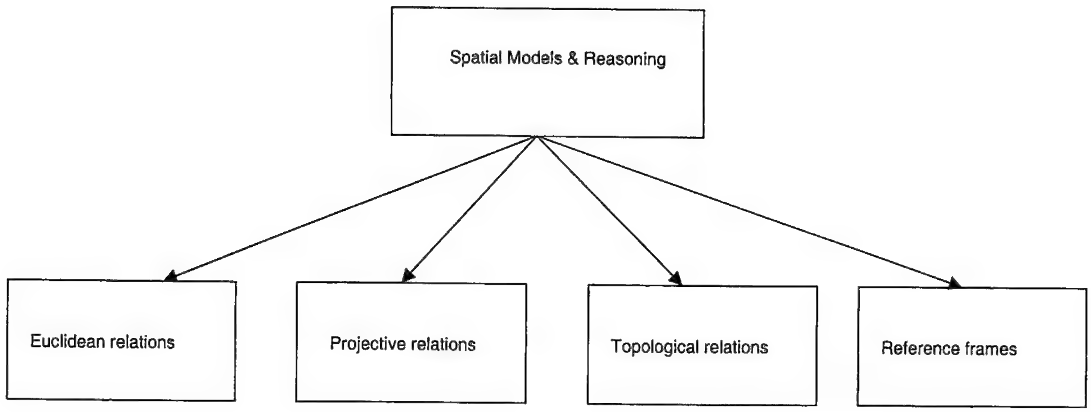


Figure 26. *Humans construct mental models that represent Euclidean, projective, and potentially topological relations. They build these mental models using three main types of reference frames (intrinsic, relative, and absolute).*

Humans organize the relations of a spatial model according to a spatial reference frame, that is, a system of three co-ordinate axes: the above/below, front/behind, and left/right axes, with origin at the reference object (Boudreau, et al., 2000; Boudreau & Pigeau, 2001). Humans can use three types of spatial reference frames to perceive or represent spatial relations (Levinson, 1996; Logan, 1995; Taylor & Tversky, 1996): (1) An intrinsic or object-centered reference frame, (2) A relative or viewer-centered reference frame, and (3) An absolute or environmental reference frame. Figure 27 illustrates these reference frames. In an *intrinsic* reference frame, humans represent spatial relations (such as relative locations) with respect to the intrinsic sides of an object or a person, that is, from the three orthogonal axes: front/behind, above/below (i.e., head/feet), and left/right axes. The ease of locating objects relative to those axes depends on body asymmetries (see namely, Franklin & Tversky, 1990). Objects located on the above/below axis are easier to locate than objects located on the front/behind axis. In turn, objects located on the front/behind axis are easier to locate than objects located on the left/right axis. In Figure 27, the aircraft's intrinsic axes define an intrinsic reference frame.

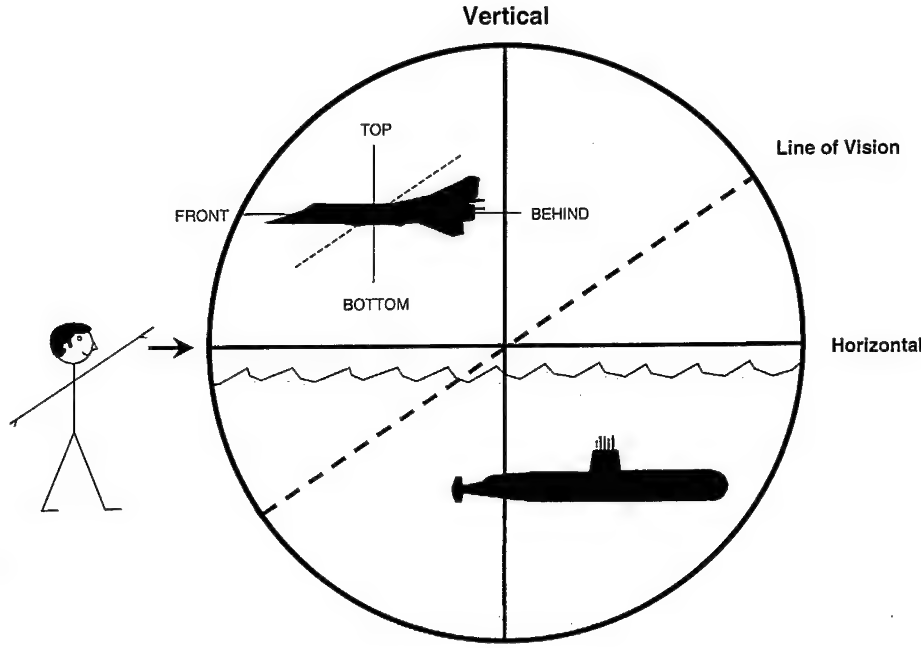


Figure 27. Illustration of three types of spatial reference frames. The aircraft's intrinsic axes specify an intrinsic reference frame. The person's physical axes specify a relative reference frame. The Cartesian coordinates specify an absolute reference frame.

In a *relative reference frame*, humans represent spatial relations (e.g., locations) with respect to their physical coordinate axes projected onto another object or person. These axes correspond to the above/below (i.e., head/feet), front/back, and left/right axes of the person. As illustrated in Figure 28 using a relative reference frame, the relative positions of the ships depend on each person's viewpoint. For person A, the Perry is in front of the Knox. For person B, the Knox is in front of the Perry. For person C, the Perry is to the right of the Knox. Spatial reference frame models make for the relative reference frame similar predictions as for the intrinsic reference frame (see namely, Bryant, Tversky, & Franklin, 1992; Franklin & Tversky, 1990; Logan, 1995).

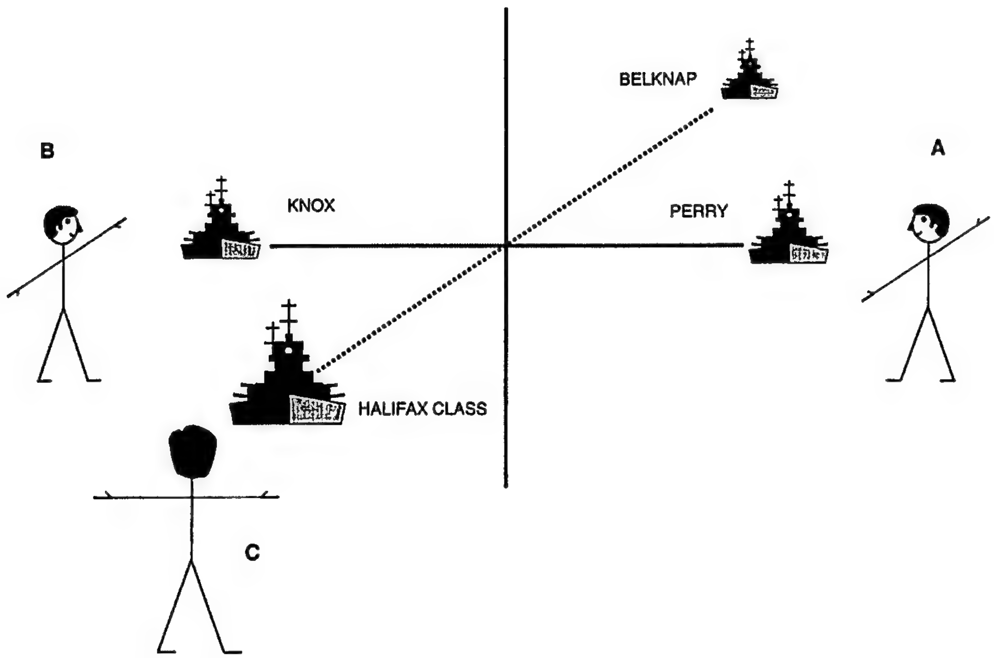


Figure 28. *Using a relative reference frame, the relative position of the ships depends on each person's viewpoint. For A, the Perry is in front of the Knox. For B, the Knox is in front of the Perry. For C, the Perry is to the right of the Knox.*

Relative reference frames affect the difficulty of identifying spatial locations from different points of view (Maki & Marek, 1997). Relative reference frames also affect the perspective from which humans will imagine a three-dimensional mental model. Using a relative reference frame, humans may view a particular facet of a three-dimensional mental model rather than a complete three-dimensional model.

In an *absolute reference frame*, humans represent spatial relations relative to fixed coordinate systems, such as, geographical bearing (latitude, longitude), gravitational axes, or Cartesian coordinates. These coordinate systems are independent of a viewer's perspective or the intrinsic axes of an object or a person. As illustrated in Figure 29, the use of an absolute reference frame insures that humans perceive and represent spatial relations among physical entities independently of their own perspective (see for example, Franklin, Tversky, & Coon, 1992; Taylor & Tversky, 1996). These absolute reference frames also allow an integrated view of the relations among entities in three-dimensions such as those that characterise a warfare area.

Absolute reference frames are very important for sharing and communicating spatial models among members of the OR team. If OR team members represent

a spatial model from an absolute reference frame, then each OR team member can have access to a complete mental model of three-dimensional spatial relations. In contrast, if members of the OR team use a relative reference frame, then other members will be required to use the same perspective or integrate different perspectives to share their spatial model. Taking another person's perspective involves two different processes: (a) changing one's mental position relative to another person's viewpoint of the spatial model (Schober, 1995), or (b) rotating one's spatial model relative to another person's viewpoint. In both cases, the change of viewpoint may involve a form of mental rotation (Boer, 1991; Easton & Sholl, 1995; Robertson, Palmer, & Gomez, 1987). Similar processes apply to the mental representation of maps in different perspectives (Péruch & Lapin, 1993). Thus, there should be less mental effort in using an absolute reference frame when constructing a team spatial model because all different viewpoints are comprised within an absolute reference frame.

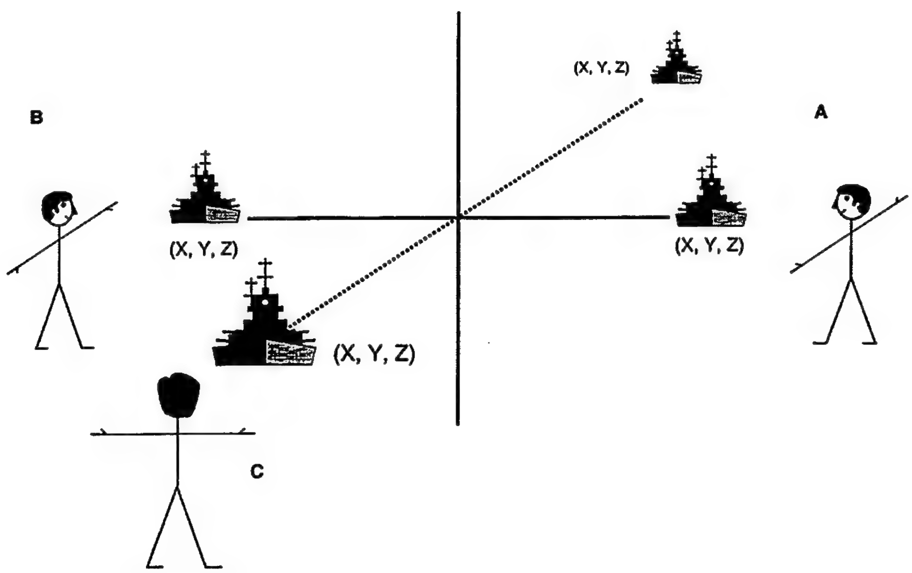


Figure 29. *Using an absolute reference frame, Cartesian coordinates or geographical bearings define the relative position of the ships irrespective of each person's viewpoint.*

In practice, the OR team members should be mentally representing an absolute reference frame because it is required for surface plotting, that is, for specifying the relative location of military units and for planning navigation routes. Surface plotting involves geometrical and mathematical calculations that may influence the metric precision of spatial models. If this is the case, the OR team's spatial models would reproduce the metric relations among military entities. Studies show that spatial models reproduce Euclidean relations. A research issue would be to determine whether spatial models reproduce metric

relations among entities relative to absolute reference frames as these reference frames are consistently presented on tactical displays.

4.3.1.2 Temporal models

Temporal models consist of ordered sequences of spatial models that correspond to the temporal order of the situations. Temporal models represent actual situations as they are unfolding. Actual situations can be novel and others prototypical and mental models represent both novel and prototypical situations (see Figure 30). Mental models can also represent hypothetical situations, that is, past situations as they could have occurred and future situations as they may occur. (Johnson-Laird, 1983).

Some temporal models of past hypothetical situations are called counterfactual models (Byrne, Culhane, & Tasso, 1995). Counterfactual models represent past situations that humans recreate in a way that counters the actual facts. Naval officers can use counterfactual models to reconstruct past military situations in order to generate different military outcomes to a tactical situation.

Temporal models of future situations are important during tactical planning because commanders generate mental models of hypothetical courses of action and because the OR Command row are continuously planning future courses of action based on possible enemy intentions and actions. Actual and past tactical situations may provide a basis for creating temporal models of future hypothetical situations.

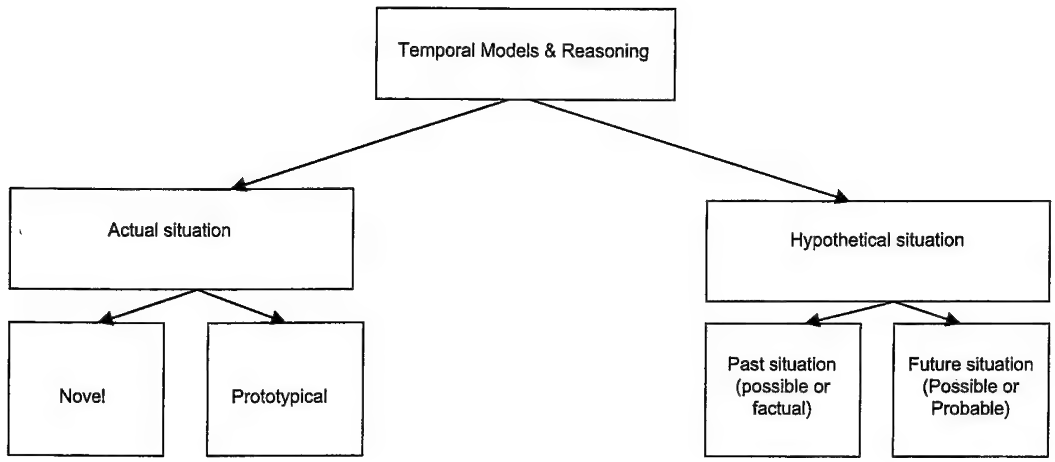


Figure 30. *Temporal models and temporal reasoning apply to actual situations and hypothetical situations.*

4.3.1.3 Kinematic models

In addition to the properties of spatial models and temporal models, as illustrated in Figure 31, a kinematic model represents the movements of entities such as translations (Easton & Sholl, 1995; Freyd, 1983), rotations (Boer, 1991; Easton & Sholl, 1995; Piaget & Inhelder, 1963), and the velocity of spatial entities (Fischer, Hickey, Pellegrino, & Law, 1994; Harwood, Wickens, & Kramer, 1986). Humans run kinematic models in real time when they construct these mental models by perceiving the motion of entities. Figure 31 illustrates aspects of kinematic models. Figure 32 illustrates a kinematic model applied to entities navigating in space. Kinematic models can represent movement that is not actually perceived but implied (Freyd, 1983; Park & Gittlelman, 1995). Freyd (1983) has shown that humans can represent kinematic models from static stimuli that provide motion cues (for example, the picture of an aircraft in mid air directed towards an airbase). Likewise, Gentner & Stevens (1983) and Park & Gittlelman, 1995) have shown, for electronic troubleshooting tasks, that humans can imagine or infer movement related to the electronic flow of current within circuits and their change over time. These inferred motions are related to the person's understanding of the functions of physical systems.

Although humans can infer motion, kinematic models are easier to construct from movement that is actually perceived or from dynamic visual displays.

Dynamic visual displays simulate actual visible movement as well as non-visible movement such as electronic flow. Park and Gittlelman (1995) have investigated the effects of simulated motion cues on the formation of kinematic models. They have shown that simulated motion cues in visual displays are more effective than static motion cues in facilitating the formation of kinematic models. When humans form kinematic models from static motion cues, they must make inferences about the actual motion from the static cues.

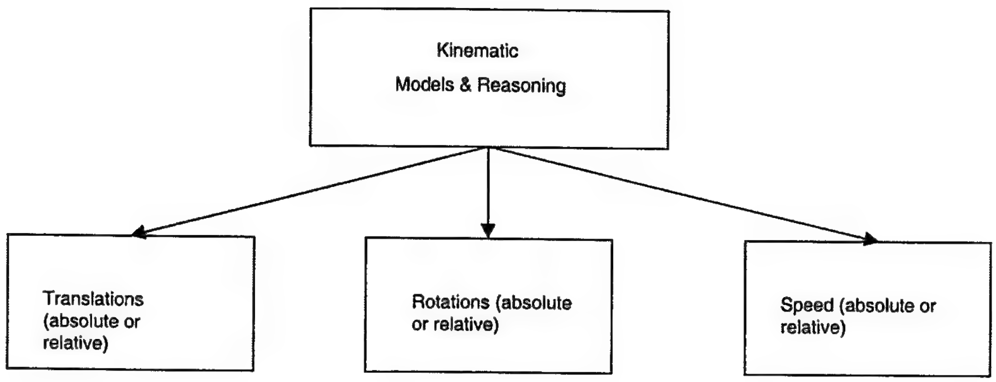


Figure 31. *A kinematic model represents motion such as translation, rotation, and speed of entities. These aspects of kinematic models can be absolute when they apply to a single object, or relative when they apply to an object relative to another.*

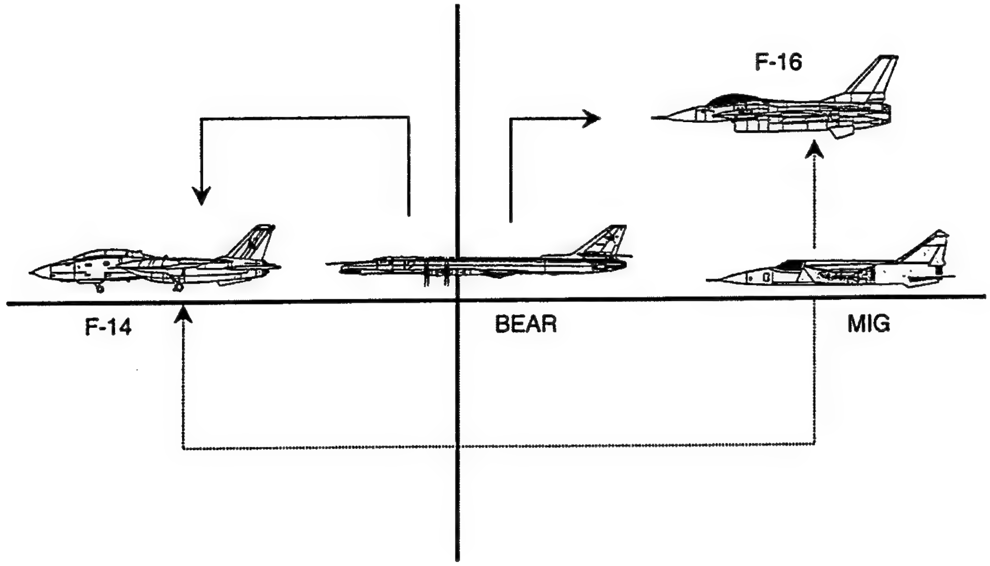


Figure 32. A kinematic model represents the motion, distance, and speed of entities relative to one another. It can also represent the motion, distance, and speed of a single entity relative to a point of arrival.

Such inferences are not required when using dynamic visual displays. Thus, dynamic visual displays are more effective in aiding the formation of kinematic models than static motion cues (Park & Gittlelman, 1995).

Kinematic models are important for the OR team members because they are required to perceive and /or represent movement of the air, surface, and subsurface units. Furthermore, the relative speed (time and distance) of moving units is essential in determining the nature of units and/ or their degree of threat. However, there are few studies that have investigated kinematic models (Freyd, 1983; Park & Gittlelman, 1995).

4.3.1.4 Dynamic models

Dynamic models comprise the spatial, temporal, and kinematic properties of the above mental models. In addition, dynamic models represent physical systems, and/or causal relations between objects or events. Scientists have investigated dynamic mental models in three different ways: (1) as intrinsic properties of mental models, (2) as mental models of physical systems, and (3) as mental models of causal relations (see Figure 33).

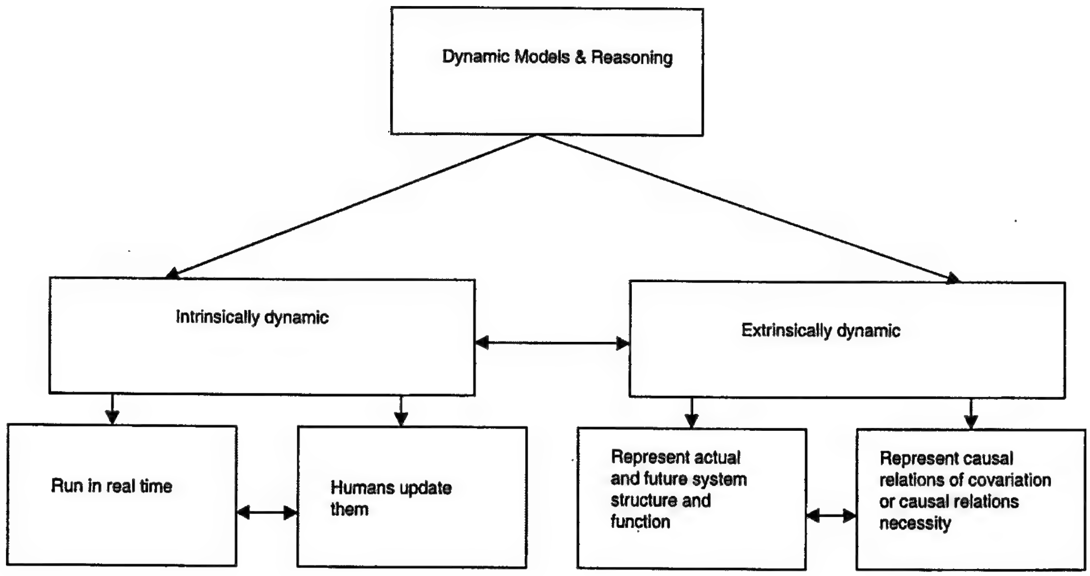


Figure 33. *Mental models are intrinsically dynamic in the sense that humans run them in real time and update them continuously. Mental models are also extrinsically dynamic in two senses. One is that they represent actual and future system structure and function. The other is that they represent causal relations of covariation or causal relations of necessity.*

Intrinsic properties of mental models. Mental models are intrinsically dynamic in two senses. One is that humans construct mental models and run them in real time. The other is that humans can update mental models by recursive revision (see Figure 34) to represent the changing aspects of the environment (Johnson-Laird, 1983). These dynamic properties of mental models are very important for the OR team members because they must maintain and update situation awareness of the different warfare areas (Matthews et al. 1999a, b). *Mental models of physical systems* represent four forms of knowledge (Gentner & Stevens, 1983; Tenney & Kurland, 1988; Rouse et al., 1992); one pertains to the *structural components* of a physical system such as the component parts of the OR and their relations (Kieras & Bovair, 1984; Tenny & Kierland, 1988); another pertains to the functions of a physical system (Kieras, 1984: Kieras & Bovair, 1984; Tenny & Kurland, 1988). A third form of knowledge pertains to the hypotheses that humans generate to predict future system states and functions (Rouse et al., 1992; Williams, Hollands & Stevens, 1983). A fourth form of knowledge refers to the user's knowledge of the methods to perform a task with the system (Kieras, 1988). Figure 35 illustrates structural and functional components of a mental model of a physical system.

34a.

34b.

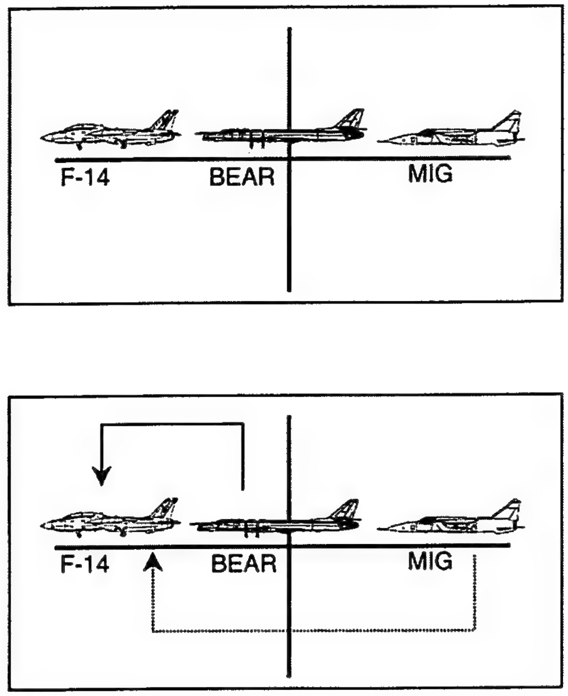


Figure 34. *Figures 34a and 34b represent two consecutive stages in the construction of a mental model.*

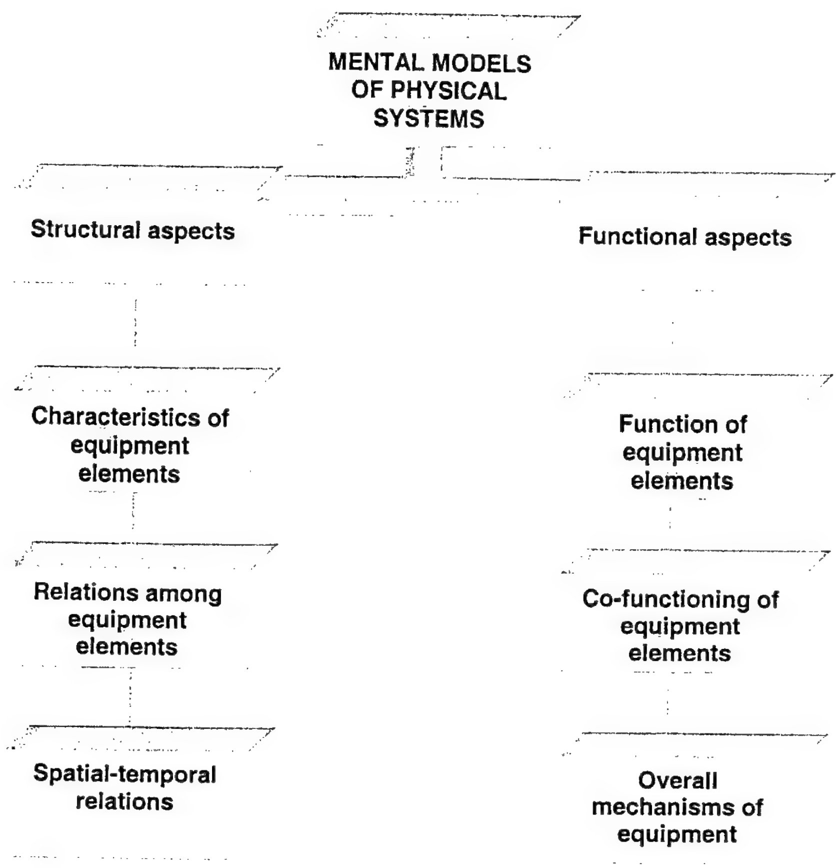


Figure 35. *Structural and functional aspects of mental models of physical systems.*

Dynamic models enable humans to represent various physical systems (Gentner & Stevens, 1983; Hanish, Kramer, & Hulin, 1991). These physical systems include *large systems operations* such as manufacturing systems, refineries, nuclear power plants, robotic systems in space, and C2 systems. Scientists of the human factors community have addressed the nature of mental models of large systems operations. Physical systems also include small systems operations such as electronic systems and mechanical systems. For these physical systems, humans construct device models (Gentner & Stevens, 1983; Park & Gittelman, 1995). Device models are a subset of dynamic models that humans construct for a physical system based on its perceived structure and functions (Norman, 1983).

A causal model represents a set of possible factors that may have a necessary relation with an effect(s) as in the case of causal models of necessity (see

Figure 36) or that may covary (or correlate) with an effect as in the case of covariation models.

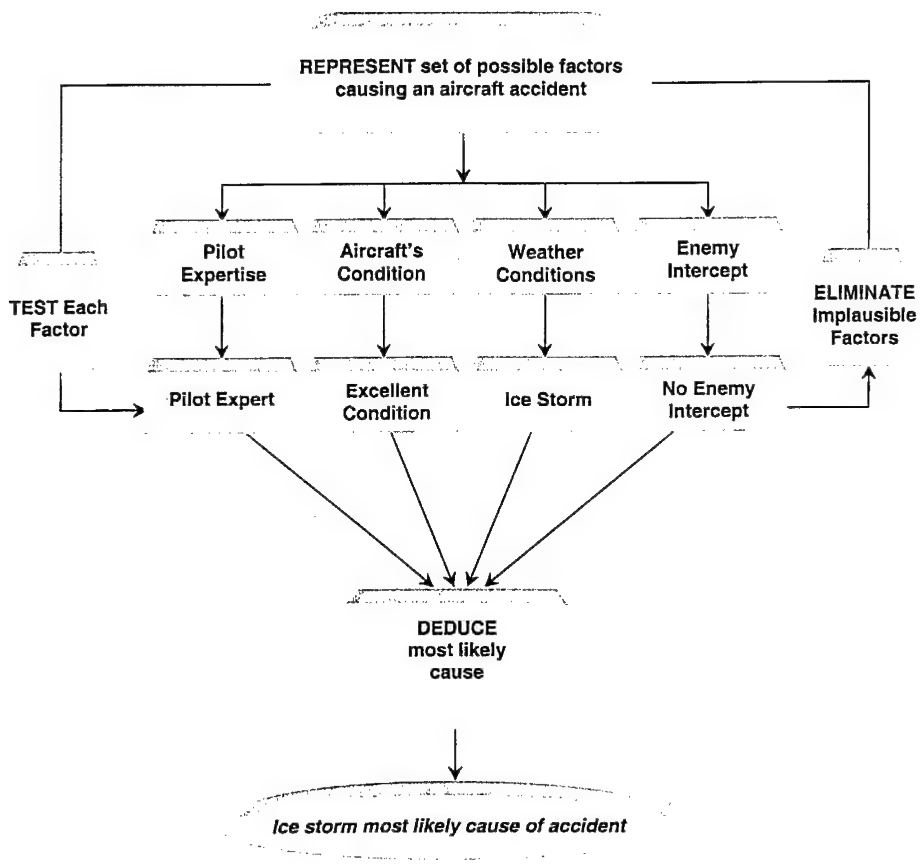


Figure 36. *Causal reasoning involves three cognitive activities: (a) the representation of hypothetical factors that may cause a given event such as an aircraft accident; (b) testing the effects of each factor in order to eliminate implausible factors; and (c) deducing the most likely factor that may have caused an event.*

Humans may use one or both types causal models. Using a causal model of necessity, humans generate and test hypotheses about factors that would constitute necessary causes of an effect. Using a covariation model, humans seek generalities from consistent covariations. Ahn, Kalish, Medin, and Gelman (1995) investigated whether humans use either model in a series of experiments on causal attribution. They showed that humans search and prefer factors that lead to causal necessity rather than factors that support covariations. Table 6

summarizes the main properties of causal models. The OR team members require causal models for the maintenance and repair of physical systems such as mechanical and electronic systems. In practice, the OR team apply causal models for causal reasoning (see Figure 36). Causal reasoning involves the four following cognitive processes.

1. Constructing a mental model of the hypothetical factors that may lead to a given effect.

2. Formulating hypotheses concerning the effects of the factors.

3. Testing the effects of the factors individually or in combination to determine the necessary and sufficient causes of an effect.

4. Deducing the factor(s) or the most plausible factor(s) that may account for an effect.

Table 6. Main properties of a causal model of necessity and a covariation model

CAUSAL MODEL OF NECESSITY	COVARIATION MODEL
Causality is based on necessary and sufficient conditions to account for an effect.	Causality based on patterns of correlation that lead to inductive conclusions.
Conclusions can be probabilistic or certain.	Conclusions are probabilistic and uncertain.
Causality is fundamentally different from covariation or correlation.	Covariation is not fundamentally different from correlation.

With experience, some of these processes may be short-circuited. In an emergency situation, the OR team could reconstruct a causal model constructed in the past to account for a given effect. Alternatively, since many emergencies are unpredictable, they would require the creation of a totally new causal model for diagnostics. In such cases, the OR team would apply each of the four cognitive processes involved in causal reasoning. Klein (1997) considers causal reasoning (also called diagnostic reasoning) as an essential component of decision making. Klein argues that a causal model would form a critical basis for selecting courses of action when situations are uncertain. Uncertain situations would trigger alternative hypotheses regarding the nature of the situations. The most likely hypothesis would then form a critical basis for selecting appropriate courses of actions. Klein also argues that causal models involve the reconstruction of past events. In turn, this process would involve counterfactual models. For example, the OR team would use a counterfactual model to reconstruct past military situations as they might have happened, and thus provide a causal explanation of the past military situations

4.3.1.5 Image models

An image model is a particular view of a mental model. That is, an image model represents a facet of a three-dimensional spatial model, a kinematic

model, or a dynamic model. Humans conceive image models from a single viewpoint that is viewer-centered rather than viewer-independent. Image models thus involve relative reference frames. Viewer-centered dependence occurs for small-scale spaces, such as scenes accessible to the immediate field of vision, as well as large-scale spaces such as scenes that go beyond the immediate field of vision (Dwadkar & McNamara, 1997; Taylor & Tversky, 1996). There are various generic properties of mental images that humans can apply when constructing an image model. One property is the representation of mental images in *long-term* and *short-term memory*. Kosslyn's theory of mental imagery represents imagery as two storage systems (Kosslyn, 1973, 1980, 1987; Kosslyn, Ball, & Reiser, 1978). One storage system encodes mental images as visual and spatial memories in long-term memory. The other storage system encodes mental images temporally in short-term memory, that is, in a visual buffer.

As in the case of mental models, a generation process retrieves visual or spatial images sequentially from long-term memory for temporary display in the visual buffer. The generation process may also activate the mental images globally from perception. A second property of mental images pertains to their *spatial* and *visual attributes*. Humans can access the spatial attributes of imagery through any sensory modality: visual, haptic (by touch), and auditory. Thus, there are common spatial images underlying any modality. However, some visual attributes of imagery, such as color, are unique to the visual modality, that is, they share many of the products of visual perception but not those of other sensory modalities. Neurophysiological evidence supports the spatial and visual attributes of imagery (for example, Roland & Friberg, 1985).

A third property of mental images pertains to their *hierarchical structure*. Complex mental images are organized into hierarchical components. For example, a mental image composed of an hourglass figure of two triangles. In turn, the mental image of each triangle consists of units such as lines and angles. Mental maps, that is, the mental representation of large-scale spaces, also appear to have the hierarchical structure associated with mental images (McGuinness, 1989, 1992; McNamara, 1991). Certain systematic distortions arise because of that hierarchical structure (McNamara, 1986). For example, humans rely on higher order information about counties rather than geometric relations (such as distances) to judge the relative positions of cities.

A fourth property of mental images pertains to their capacity to represent certain *Euclidean relations* (such as dimension and distance) and *projective relations* (such as translations and rotations). Cognitive studies on spatial images indicate that images reproduce one-dimensional relations (such as A is above B, B is above C) as linear arrays (Handel, DeSoto, & London, 1968; Huttenlocher, 1968; Mynatt & Smith, 1977; Newstead, Manktelow, & Evans, 1982). Moreover, experiments on image scanning indicate that spatial images preserve inter-object Euclidean relations, such as distance and scale (Kosslyn, 1980; Kosslyn & Pomerantz, 1977; Kosslyn, Ball & Reiser, 1978). For example, spatial images in the visual buffer reproduce distances among objects as if they were actually perceived. Spatial images in the visual buffer can be

enlarged or reduced in scale (McGuinness, 1989, 1992). Spatial images also represent projective relations such as translations (Easton & Sholl, 1995) and rotations (Sheppard & Cooper, 1982).

Humans can update the viewpoint of spatial images by rotating the image (Boer, 1991), or by changing their spatial reference frame (Péruch & Lapin, 1993). However, the use of spatial images imposes much mental effort when humans are required to change the viewpoint of the spatial image. Thus, it would be more efficient for humans to use three-dimensional spatial models rather than spatial images to represent the physical environment. When spatial images represent large-scale spaces or scenes, they are called mental maps (Siegel & White, 1975; Taylor & Tversky, 1996). Mental maps may not preserve the Euclidean properties of real space such as distances. Rather, cognitive scientists argue that mental maps have a hierarchical structure similar to that of semantic knowledge (Kuipers, 1978, 1982; McGuinness, 1989, 1992; McNamara, 1986, 1991). The hierarchical structure of mental maps would consist of hierarchical relations among entities of the environment, such as the locations of geographical cities within counties, counties within states, and states within countries. The hierarchical structure of mental maps would influence the representation of Euclidean relations, such as the estimate of distances (McNamara, 1986, 1991) and the location of entities in the environment

In conclusion, given experimental evidence (Boudreau et al., 2000; Byrne & Johnson-Laird, 1989; Johnson-Laird & Byrne, 1991, 1993), it is highly likely that physical mental models represent human understanding of aspects of the physical world. This includes the spatial, temporal, kinematic, and causal relationships among physical entities. Figure 37 illustrates the hierarchical structure of physical mental models. Humans can construct each type of physical mental model with or without the aid of mental imagery. These physical mental models have conceptual equivalents. Any physical mental model can include abstract entities, their attributes, and their relationships. Given the above properties of physical models, tactical displays should be effective to the extent that they map onto the geometrical properties of these models. For example, the OR team members build geographical models for plotting positions or general operating plots for spatial navigation. The tactical displays should also compensate for the potential inaccuracies (or distortions) related to the use of image models instead of spatial models. However, is the use of effective tactical displays sufficient to insure adequate mental representations? It is possible, but training methods that enhance the construction of physical models should provide a complementary approach to the design of effective tactical displays.

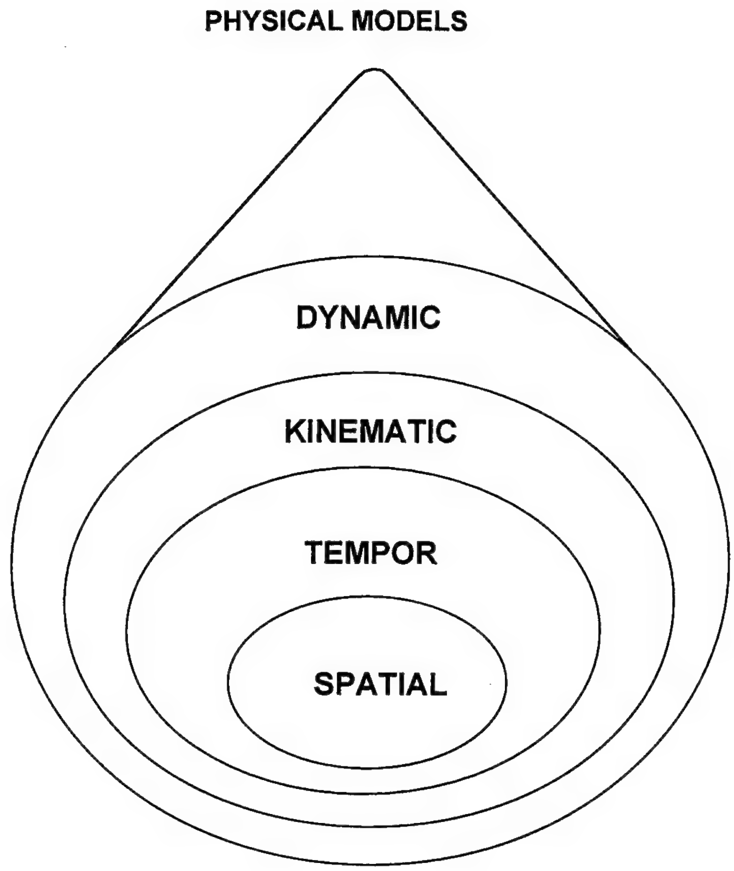


Figure 37. *Hierarchical structure of physical mental models. Each ellipse represents a type of mental model that is integrated within a more complex mental model. Humans can use mental imagery to support each type of mental model. However, mental images are neither necessary nor sufficient to construct physical mental models.*

4.3.2 Conceptual mental models

Conceptual mental models are abstract mental representations of discourse among humans. As in the case of physical mental models, conceptual mental models consist of a set of symbolic tokens, their attributes, and their relationships. Conceptual mental models differ from physical mental models in that humans can produce them through imagination without having any basis in the physical world. There are six types of conceptual models where the first four are deductive mental models (see Figure 38):

(1) Hypothetical models, (2) Propositional models, (3) Categorical models, (4) Relational models, (5) Inductive models, and (6) Analogical models.

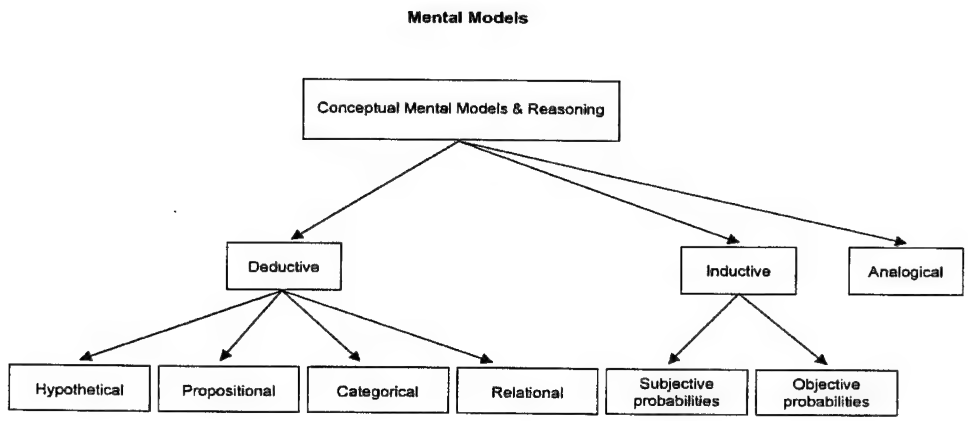


Figure 38. *Conceptual mental models include deductive, inductive, and analogical mental models*

4.3.2.1 Hypothetical models

Hypothetical models consist of a set of hypotheses that humans generate automatically in response to uncertain, possible, or probable events (Stevenson & Over, 1995). Humans also generate hypotheses to understand surprising and novel events (Bruner, Goodnow, & Austin, 1956). The hypothesis-assessment approach argues that humans construct hypotheses and evaluate their plausibility in light of external observations and semantic knowledge (McDonald, Samuels, & Rispoli, 1996). For example, when on watch, a given set of events on a radar display will trigger a set of hypotheses regarding the possible identity or meaning of the signals: the signals may correspond to noise, military units, and/ or a civilian units (see Figure 39). The OR team would start by creating general hypotheses regarding the possible identity of the signals. Semantic knowledge of naval operations would help rule out implausible hypotheses. From the set of plausible hypotheses, the OR team members would then generate specific hypotheses relative to the probable identity of the signals. At each of these levels of conceptualization, the OR team would elaborate and revise the hypothetical models that they have constructed to account for the perceived radar (or sonar) signals.

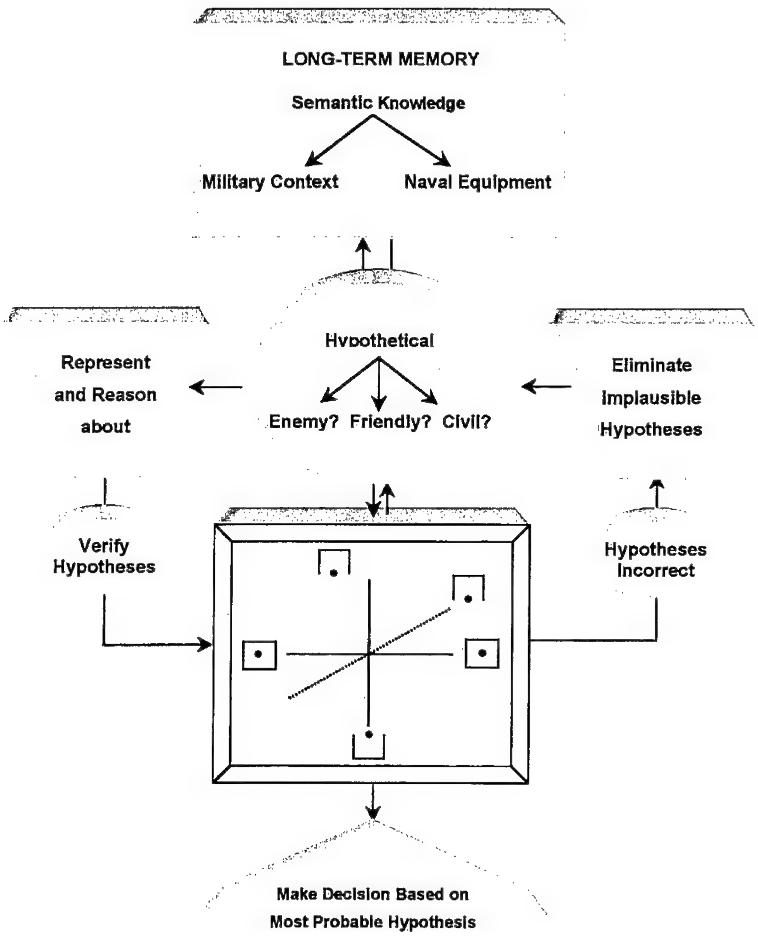


Figure 39. *A set of unknown tactical symbols will trigger hypotheses regarding the possible identity of the symbols. Hypothetical mental models will represent alternative hypotheses. For example, an unknown tactical symbol will trigger two hypotheses: (1) it is either a friendly target, or (2) it is an enemy target. Humans will then verify these hypotheses based on observed data and semantic knowledge. If the hypotheses are correct, these will provide a basis for making decisions. If the hypotheses are incorrect, humans will update their mental model and construct hypotheses that are more plausible.*

Hypothetical models, like all mental models, have an intrinsic updating function that takes into account physical information and semantic knowledge. The two sources of information are important because they help verify hypotheses and construct new ones when prior ones are deemed invalid. Hypotheses are an intrinsic part of temporal models of future or past situations. Hypothetical models and temporal models would thus work in tandem.

4.3.2.2 *Propositional models*

Propositional models represent propositional connectives such as 'and, or, if, not' that occur spontaneously during discourse among humans (Byrne & Johnson-Laird, 1992). Propositional connectives are relations that humans establish spontaneously between assertions or hypotheses during discourse (Johnson-Laird, Byrne, & Schaeken, 1992). For example, this radar contact is either an enemy aircraft or it is a friendly aircraft but not both. Assertions have a truth-value, that is, they are either true or false. When situations are uncertain, assertions are either possibly true or possibly false. As illustrated in Figure 40, the following assertions may be true: either the Mig will engage the F-14, or the Bear will engage the F-14. Humans and Naval officers construct propositional models when they are required to think and reason about uncertain assertions or events. For the OR team, the use of propositional models is emphasised during operational planning where various possible enemy courses of action must be compared to own courses of action. Propositional models represent three main propositional connectives: (a) the conjunction "and", (b) the disjunction "or", and (c) the conditional "if". We can define the meaning of propositional connectives in terms of the truth-values of the assertions related by these connectives.

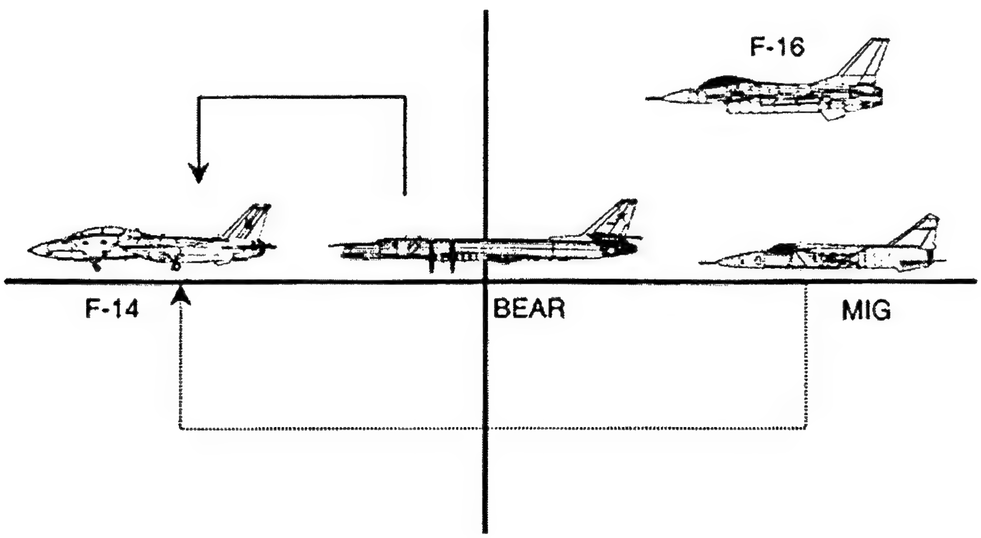


Figure 40. *Example of a mental model of disjunction: (a) either the Bear will engage the F-14, or (b) the Mig will engage the F-14. The arrows represent the possible navigation path of the Bear and the Mig.*

The *conjunction* "and" relates any two assertions "P and Q". If both assertions are true then the conjunction of the two assertions is also true. If only one of the assertions is false, or if both of them are false, then the conjunction of the two assertions is also false. For example, a conjunction of two assertions is false if it states that "a radar signal corresponds to a friendly unit and is engaging own units".

A similar definition is given to the meaning of "or" which can be an inclusive *disjunction* or an exclusive disjunction and is true provided that at least one of the assertions is true. An *inclusive disjunction* relates any two assertions "either P or Q or both". For example, the following two assertions represent an inclusive disjunction: (a) either the Bear will engage the F-14, or (b) the Mig will engage the F-14, or both courses of action may be true. One of the assertions may be true or both may be true.

The inclusive disjunction is false if both of the assertions are false. For example, the ORO(s) can generate a set of hypothetical courses of action. However, there is not necessarily a unique course of action, but rather alternative courses of action that may be true (as illustrated in Figure 40). One or more of the hypotheses may be true.

An *exclusive disjunction* "P or Q but not both" is true only if one of the two assertions is true. The exclusive disjunction is false if both assertions are false. For example, if a sonar signal is unknown, an officer will create a set of alternative hypotheses to account for the possible identity of the signal: either the signal corresponds to a friendly submarine (P), or an enemy submarine (Q) but not both. In some cases, the choice of an alternative hypothesis will depend on a *conditional* relation between an antecedent condition (such as a rule of engagement) and a consequent condition (such as engage), for example: "if the enemy takes this course of action then this rule of engagement". Johnson-Laird (1986) has specified the set of conditional relations that humans use to reason about conditional statements.

Conditional models represent the construction of a scenario in which an antecedent event, a consequent event, and a relation between the two that corresponds to the meaning of the conditional. Conditional relations based on "if" have different meanings (see Johnson-Laird, 1993). These meanings include logical implications (Taplin, 1971; Johnson-Laird, 1993; Johnson-Laird & Byrne, 1991), causal relations (Cummins, Lubart, Aknis, & Rist, 1991), and deonic relations such as permissions or obligations (Cheng & Holyoack, 1985). The meaning of conditionals depends on the nature of the sentences (or propositions) and the person's interpretation of the sentence.

4.3.2.3 Categorical models

The OR team members are required to categorize sets of entities from stimuli presented on tactical displays. They can construct categorical models independantly or in conjunction with hypothetical or propositional models (see Figure 41). Categorical models assume a hierarchical structure of semantic knowledge. There are three types of categorical models: (a) set models, (b) set-theoretic models, and (c) meta-theoretic models (Johnson-Laird, 1983). The three types represent a hierarchy of categorical models that are increasingly abstract. Matthews et al. (1999a) have observed, from their cognitive task analysis, a similar structure of information representation by the OR team.

Mental Models

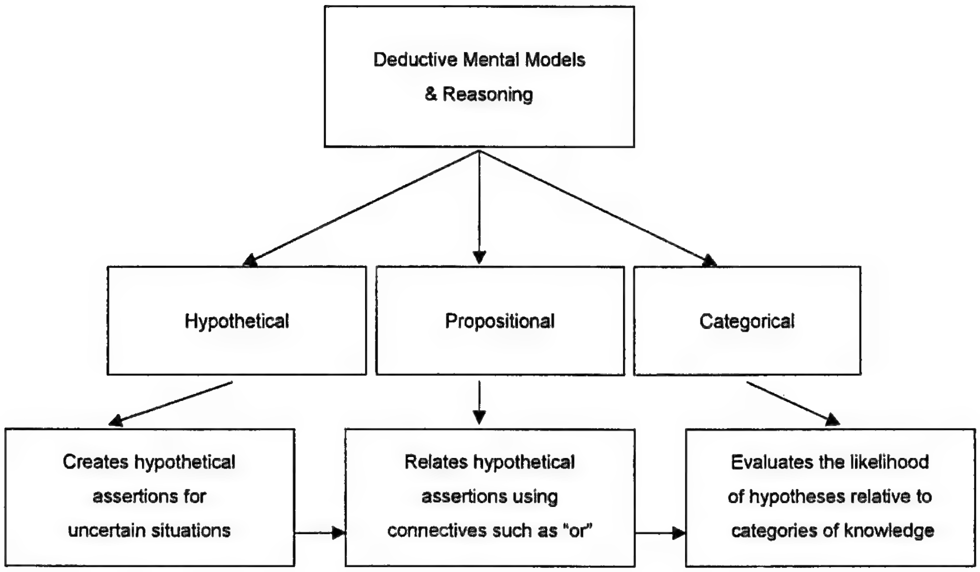


Figure 41. *Humans can construct hypothetical, propositional, and categorical models independently from one another. These three mental models intervene in the process of reasoning about hypotheses that apply to possible or uncertain situations.*

Set models represent quantified relations between sets of entities and their properties. Quantified relations such as 'all', 'some', 'none', and 'any' (see Figure 42) specify linguistically, the proportions of entities in a given set (such as Migs) that one can identify with the entities of another set (such as enemy aircraft). For example, the assertion "most Migs are enemy aircraft" represents linguistically the proportions of Migs that one can identify with the set of enemy aircraft. The OR team members use quantified relations continuously during threat assessment to identify and categorize stimuli. They may categorize sets of stimuli at different levels of a hierarchy of semantic knowledge. For example, one can compare a type of entity to a generic type, or a generic type with a category. The tactical symbols that naval personnel use in the HCF provide a categorical model because each symbol represents a set of entities. For example, a symbol may represent all the objects of a category (such as the symbol for ships), some of the objects of the category (such as the symbol for friendly ships), or none of the objects of a category (such as the symbol for aircraft). Some of the tactical symbols and the category that they represent are listed in section 10.

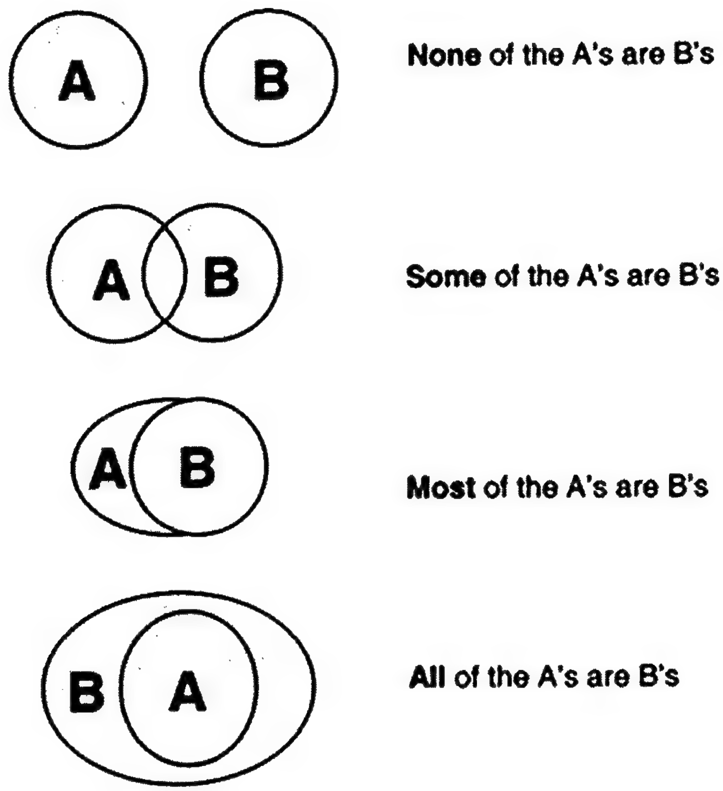


Figure 42. *Visual representation of the quantified relations none, some, most, all.*

Humans use set models for deductive inferences (Johnson-Laird, 1994a, b). For example, after identifying that a Mig is an enemy aircraft, the OR team members can make deductions concerning its possible future behavior based on the knowledge that it is an enemy aircraft. Reasoning from categorical knowledge is called syllogistic reasoning (Johnson-Laird & Bara, 1984; Johnson-Laird, Byrne, & Tabossi, 1989).

Set-theoretic models (Johnson-Laird, 1983) include a finite number of tokens representing sets. Each set represents entities, their attributes, and their relations. The content of the sets can be conceptual or physical. For example, the following set-theoretic model called "X" includes three sets that the tokens A, B, and C represent:

- Set X = {A, B, C}

Each set comprises entities, their attributes and their relations. For example:

- Set A = {air units, their attributes, and relations}

- Set B = {air and surface units, their attributes, and relations}
- Set C = {subsurface units, their attributes, and relations}

Figure 43 illustrates a set-theoretic model comprising three sets. Set-theoretic models would be very useful when OR members are dealing with complex sets of entities that would overload their working memory capacity. This is because set-theoretic models contain a finite set of tokens (for example: A, B, C) that can represent implicitly large sets of entities. The finite number of tokens thus represents an economical way of memorizing volumes of information thus reducing working memory load.

As in the case of set models, humans can use quantified relations to identify verbally the proportion of entities of any given set, for example, some of the entities of Set B are air units and some are surface units and to compare the proportion of any given set relative to another set. For example, the entities of set A may consist of air units while only some of the entities of set B may consist of air units.

Meta-theoretic models correspond to the most abstract categorical model. Meta-theoretic models represent mental models of mental models. Meta-theoretic models include a function of recursivity by which one mental model is embedded within another mental model to generate a hierarchical structure of categorical models. For example, Commanders may construct a Command theory comprising different theories of Command. Likewise, in strategic planning, they may construct categories of categories of plans, such as those that have been used during the First or Second World War.

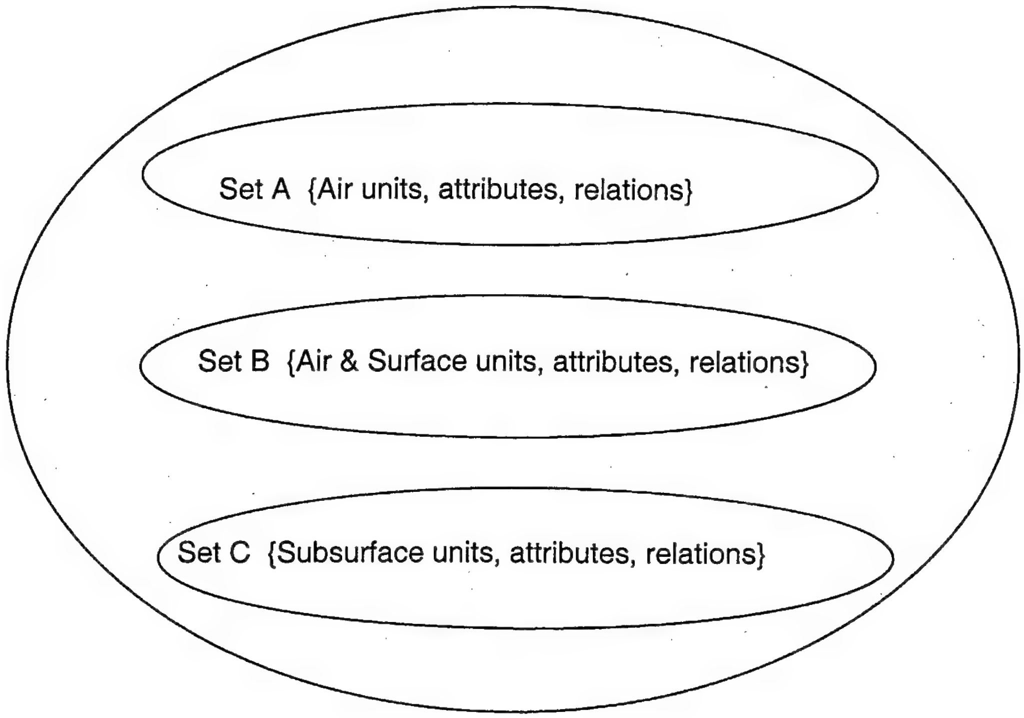


Figure 43. *Example of a set-theoretic model where Set X {Warfare areas} comprises three sets A, B, and C pertaining to the air, the surface, and the subsurface warfare areas respectively. Each set represents a complex set of entities using the minimum of symbolic tokens.*

4.3.2.4 Relational models

Relational models represent relations among entities of assertions (such as, A is faster than B) rather than relations among assertions (such as, A is faster than B, or A is faster than C) as in the case of propositional models. Relational models contain tokens such as images of aircraft or ships that represent the corresponding entities in the context discussed. The relations among the tokens consist of symmetric relations (such as, A is in the same place as B; B is in the same place as A), asymmetric relations (A is faster than B; B is slower than A) and relations of identity (A is the same as B; B is the same as A). These relations can apply to spatial contents (such as A is in front of B) or non-spatial contents (such as A is better than B). Relational models allow transitive reasoning as in the following example: If A is in front of B, and B is in front of C, then A is in front of C.

Relational models are important when OR officers are constructing physical models of space, time, movement or causality. For example, a spatial model can

specify the relative location of entities according to spatial relations such as in front, above, left. The following set of four sentences illustrates such relations.

1. A is directly left of B

2. C is directly right of

3. D is directly behind

4. E is directly behind B

Figure 44 depicts a relational model that one can construct from these. The sentences describe spatial relations among the tokens A to E. The relations among the tokens could correspond to metric relations that specify the exact location of tokens in three dimensions.

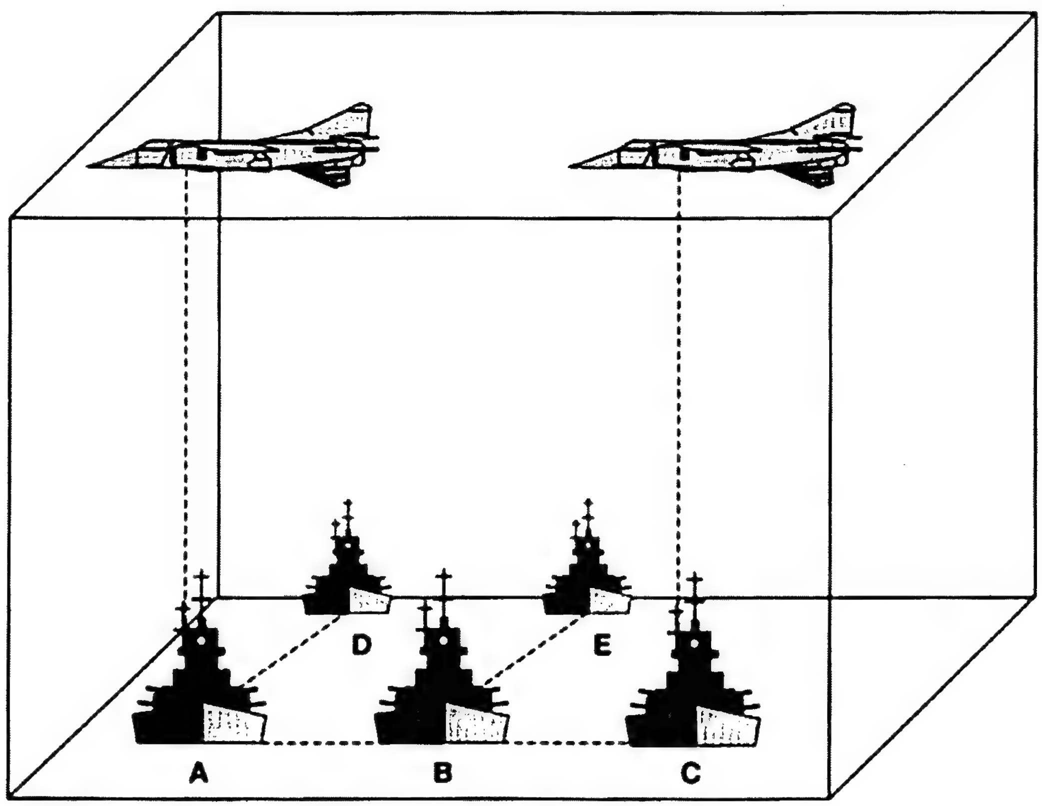


Figure 44. *Relational models represent transitive relations such as: A is directly left of B; C is directly right of B; D is directly behind A; E is directly behind B.*

4.3.2.5 Inductive models

The conceptual mental models described so far form the basis of deductive reasoning. Inductive models are at the basis of inductive reasoning. An induction is the inference of a general conclusion from a set of instances (such as objects, attributes). An inductive model represents a set of instances in support of a general conclusion and the general conclusion. The set of instances may consist in attributes that may belong to an object, or a set of objects that may belong to a category. For example, the ships 'Knox', 'Belknap', and 'Perry' belong to the category American ships. The inductive model allows inferences from the set of attributes to a given object, or the set of objects to a given category. Inductive models thus enable inferences from lower-levels of a hierarchy of semantic knowledge to higher-level ones (see Figure 45). In contrast, categorical models enable inferences from higher-levels of a hierarchy of semantic knowledge to lower-level ones. Inductive inferences are essentially probabilistic, that is, humans will have a certain degree of belief in the truth of the conclusion but they will not be certain of its necessity.

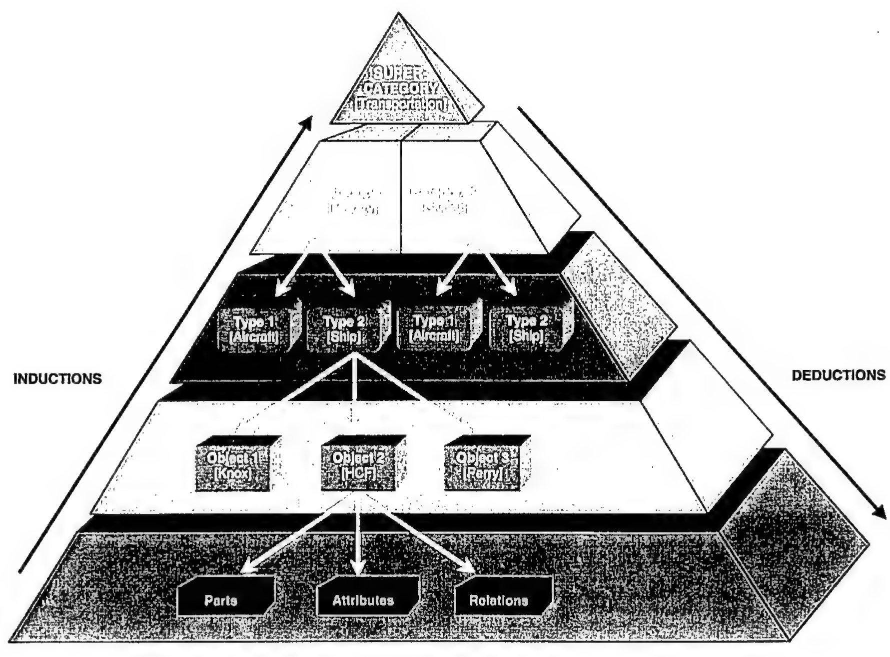


Figure 45. *Inductive models enable inferences from lower-levels of a hierarchy of semantic knowledge to higher-level ones. In contrast, deductive models (such as categorical models) enable inferences from higher-levels of the hierarchy to lower-level ones.*

McDonald, Samuels, and Rispoli (1996) argue that belief in the validity of an inductive conclusion depends on the number of instances (such as objects, attributes, and relations) that support the conclusion, and the scope of the conclusion. If there are counterexamples to the conclusion, inductive models will lead to probabilistic conclusions. Probabilistic conclusions refer to the likelihood that a sentence or a picture is true (or that an event will occur). Scientists define probabilistic conclusions in terms of objective probabilities and subjective probabilities. Mathematicians (Carnap, 1950) define objective probabilities as the extent to which an event is likely to occur as measured by the ratio of favorable cases relative to the whole number of possible cases. For example, the probability of rain (80%) given a set of atmospheric conditions. Cognitive scientists (Gigrenzer, Hoffrage, & Kleinbölting, 1991; Johnson-Laird, 1994a, b; Over and Manktelow, 1994) define subjective probabilities as the degree of belief that a conclusion (e.g., a sentence, a picture) is true or that an event will occur. The degree of belief in a conclusion will depend on the proportion of cases that support the truth of a conclusion (Johnson-Laird, 1994a, b). Humans can establish proportions using quantified relations such as "many, most, some" without using the probability calculus or natural numbers. For example, in the following argument, the quantified relation "most" represents a proportion.

- Kropotkin is a naval officer
- Most naval officers are men
- Probably Kropotkin is a man.

The meaning of "probably" in the conclusion is equivalent to saying that the conclusion is true in most cases. The Mental Models theory assumes that the degree of belief in a conclusion depends on the relative proportion of two sorts of mental models: those in which a conclusion is true (most naval officers are men) and those in which a conclusion is false (few naval officers are men). Humans estimate these proportions using quantified relations to construct the two sorts of mental models. Those in which a conclusion (such as Kropotkin is a man) is most likely to be true will occur more often than those in which it is likely to be false (such as Kropotkin is a women). The assessment of subjective probabilities should be similar for teams of individuals who share available information.

The Mental Models theory (Johnson-Laird, 1994 a, b) argues that it is important for humans to consider counter-examples when they are assessing the likelihood of an event. When humans draw a conclusion without considering counter-examples, they will base their belief in a conclusion on a priori biases and heuristics (Evans, 1989). However, there are at least three factors that constrain the consideration of counter-examples: (1) the processing capacity of *working memory*, (2) the *availability of relevant information*, and (3) the propensity of humans to be *inferential satisficers*.

Experiments based on the Mental Models theory have shown that the process of constructing alternative mental models is more difficult than the process of building a single mental model (see namely, Johnson-Laird & Byrne, 1991). Alternative mental models thus increase the load on *working memory*. This increased load on working memory occurs when humans reason or make decisions under uncertainty (Shafir & Tversky, 1992; Shafir, 1994). Shafir and Tversky (1992) define decision making under uncertainty as a process by which humans reason through alternatives: for example, either a given event may be true (P) *or* another one may be true (Q), or they may be both true. The OR team members must represent and reason about uncertainty and make choices among alternative situations. One solution to reducing load on working memory is to construct a generic although implicit mental model of alternative possibilities. The generic mental model (such as X = {A, B, C}) would contain a set of tokens that represent implicitly sets of alternatives possibilities. For example, the generic mental model {A, B, C} would contain sets A, B, and C, and each would represent a set of alternatives such as:

X= {A (a1, a2, a3), B (b1, b2, b3), C {c1, c2, c3)}.

The set A would contain the alternatives "a1, a2, a3". The set "B" would contain the alternatives "b1, b2, and b3". The set C would contain the alternatives "c1, c2, and c3". Humans could then flesh out the generic mental model when required or as required.

Availability of relevant information can influence *the number of models considered*. Johnson-Laird (1994a, b) distinguishes three strategies for retrieving information that will help consider alternatives. The first strategy is to construct a single mental model of an event containing all relevant entities, their attributes, and their relations, for example, a mental model of an event where a missile intercepted an aircraft. The second strategy would consist in manipulating the spatial and physical aspects of the event, for example, one could consider that the pilot detected the approaching missile in time and decided to eject from the aircraft before the missile reached it. The third strategy would consist in making conceptual manipulations of the mental model, for example, one could consider that friendly forces where in the vicinity of the pilot and rescued him. The objective of these types of strategies is to think beyond the given mental model of facts in order to consider remote possibilities. These model-based strategies would help consider alternative courses of events to the one that is most likely.

A third constraint on the search for alternatives is that humans are *inferential satisficers*, that is, when humans reach a credible conclusion they are likely to accept it and overlook counterexamples to the conclusion. This propensity to satisfice will yield overconfidence in the credibility of a conclusion. When situations (or problems) yield counter-examples as it is the case of inductive models, the Mental Models theory proposes that humans would overlook the counter-examples that would repudiate a conclusion. As a result, people would be more confident than justified on these difficult problems. Consequently, any

factor that facilitates the construction of counter-examples should improve performance and reduce biases in inductive reasoning.

4.3.2.6 *Analogical models*

Analogical models may help naval commanders recognize the similarities between a current tactical situation and categories of pre-planned courses of actions. These similarities may then provide a basis to solve problems regarding the actual tactical situation.

Gentner and Stevens (1983) provide a structure-mapping theory of analogical models. This theory characterizes analogical models as structure-mappings between models of two different domains; it asserts that humans can apply the generic structure of a source mental model (the known domain) to the target mental model (the current domain of inquiry) (see Figure 46). In the case of problem solving, an individual can take the structure of a solution of a problem and map it onto an other problem having similar structure although different content. For example, a kinematic model of navigation can be applied to different geographical areas.

There are at least two main sources of difficulty in constructing an analogical model. One is in finding appropriate examples for the analogy. The other is noticing when analogy is possible (Gick & Holyoack, 1983). In selecting an analogy, humans are often guided by superficial similarities between a source mental model and a target mental model (Gentner & Stevens, 1983). When humans base their choice of analogical models on superficial similarities, rather than abstract similarities, they are less likely to reach problem solution.

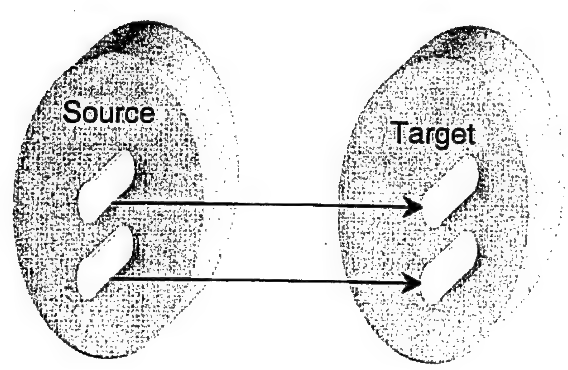


Figure 46. *A one-to-one mapping between a source mental model and a target mental model.*

4.3.3 Shared mental models

4.3.3.1 General properties of shared mental models

The concept of shared mental models refers to the knowledge that members of a team have in common to accomplish a task effectively (Cannon-Bowers, Salas, Converse, 1993; Volpe, Cannon-Bowers, Salas, & Spector, 1996). Team mental models include an understanding of the four following types of knowledge:

- the structure and functions of the equipment with which each member of a team is interacting
- the task structure, that is, an understanding of the task and the processes by which to accomplish it
- team role structure, that is, an understanding of the role that each team member plays in accomplishing a task
- an integrated structure, that is, an understanding of the relations among each of the above three types of knowledge

Physical and conceptual mental models may be shared among the OR team members (see Figure 47 for an illustration). For example, the OR team members will share spatial models of the physical environment. However, there are very few studies, if any, on physical or conceptual mental models in team performance.

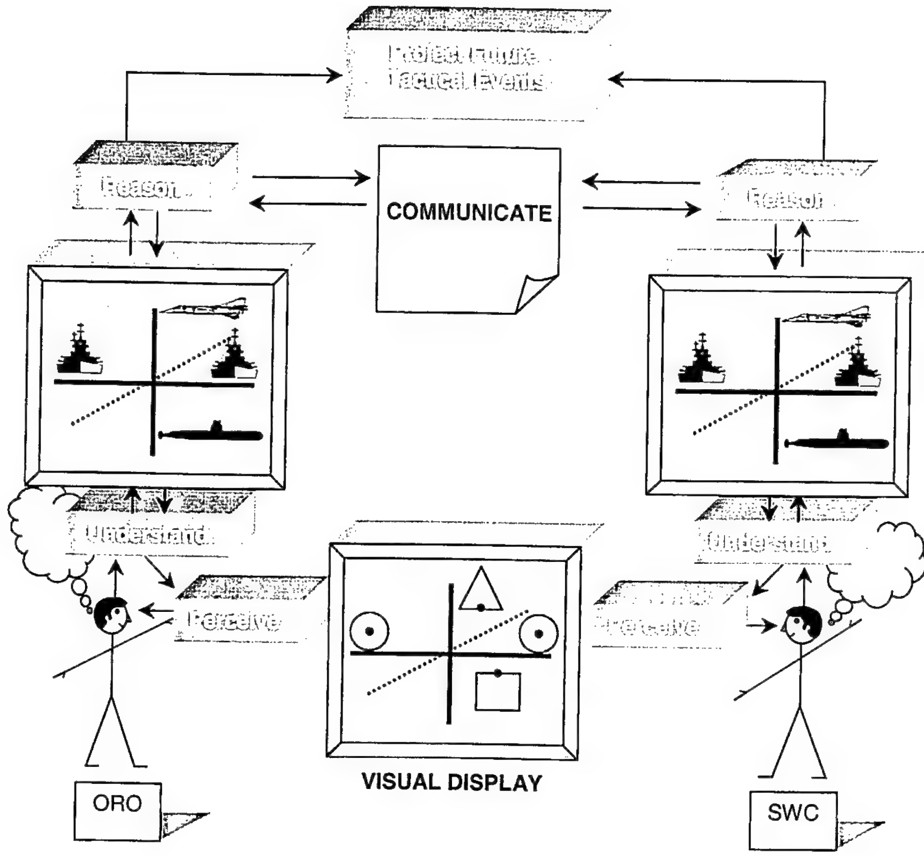


Figure 47. The Command row officers perceive stimuli from visual displays. Their comprehension of the stimuli enables them to build a mental model of the tactical situation. Naval personnel use this mental model to reason about the tactical situation, that is, to make inferences concerning future tactical events. Communication among officers will affect the way they represent and reason about the tactical situation.

4.3.3.2 Applications of shared mental models to team performance

Shared mental models can provide a viable framework for training a team of experts (Salas, Cannon-Bowers, & Johnston, 1997; Serfaty, MacMillan, Entin, & Entin, 1997). Shared mental models also account for the performance of expert teams, that is, how a team performs in optimal ways in complex decision making environments.

Grice (1975) argues that genuine communication among humans depends on the recursive representation of intentions or goals in both the sender and the receiver of a communicative act. Scientists have suggested that mental models of intentions would involve (1) the representation of one's intention(s) in a communicative interaction (for example, I want X to believe A); (2) the representation of other people's intention(s), and (3) the representation of other people as possibly being aware of one's intention(s) (Dennett, 1997; Grice, 1975; Hausser, 1997; Whiten, 1997). According to the definitions that authors have proposed, mental models of intentions represent the intention, such as a goal, of a communicative interaction that directs future actions. The theories of mental representation should specify more extensively what is really meant by the concept of intention and the scope of the "intentions" that the mental models represent.

There are at least four reasons why these mental models would be important for the OR team. First, mental models of intentions would be essential for understanding higher Command intent (Pigeau & McCann, 2000). Second, mental models of intentions would be involved in the representation of expectations among the OR team members. Third, these mental models would be essential for representing and reasoning about the enemy's possible intentions and consequent courses of action. Fourth, mental models of intentions would be essential for creating and inferring tactical and operational plans of deception. By correctly representing the enemy's intentions, commanders can create deception strategies to counter these intentions.

Scientists invoke shared mental models as a mechanism by which expert teams would cope and adapt to stressful situations where communication is often severely restricted by anticipating the needs of other team members. Likewise, training shared mental models of team role structure and task structure can reduce the effects of stress (Cannon-Bowers, Salas, & Converse, 1990, 1993; Volpe, Cannon-Bowers, Salas, & Spector, 1996). Scientists assume that expert teams under high stress rely on implicit role coordination based on shared mental models because these reduce the needs of explicit verbal communication. Teams can also adapt to high levels of stress by modifying their coordinating strategies (Serfaty, Entin, & Volpe, 1993).

4.3.4 Application of semantic representations to the OR team's awareness needs

The ORO cognitive task analysis (Matthews et al. 1999 b) identified a set of awareness needs of the OR team. These awareness needs can be categorized and related to the different types of physical and conceptual mental models and schemas. Figures 48, 49, and 50 (based on the logic of figure 24) show which types of physical or conceptual mental models and schemas the OR team is most likely to use for the various awareness needs.

Based on the OR awareness needs, the OR team members would construct spatial and kinematic models and schemas to represent and reason about different aspects of the air,

surface, and subsurface environments. They would construct temporal models and schemas to represent and manage tasks and information flow according to mission schedule and priorities. They would construct dynamic models and schemas to represent and reason about physical systems whether at a small scale (e.g., equipment of ship) or large scale (e.g., task group capability). It is most likely that the OR team constructs conceptual mental models and schemas to represent and reason about ROE, intelligence, and threats, whether these events are hypothetical, possible, or probable (see Figure 49).

All aspects of individual mental models and schemas are potentially shared among the OR team. As shown in Figure 50, shared physical and conceptual mental models and schemas should apply to a subset of the awareness needs identified by the cognitive task analysis (Matthews et al. (1999b).

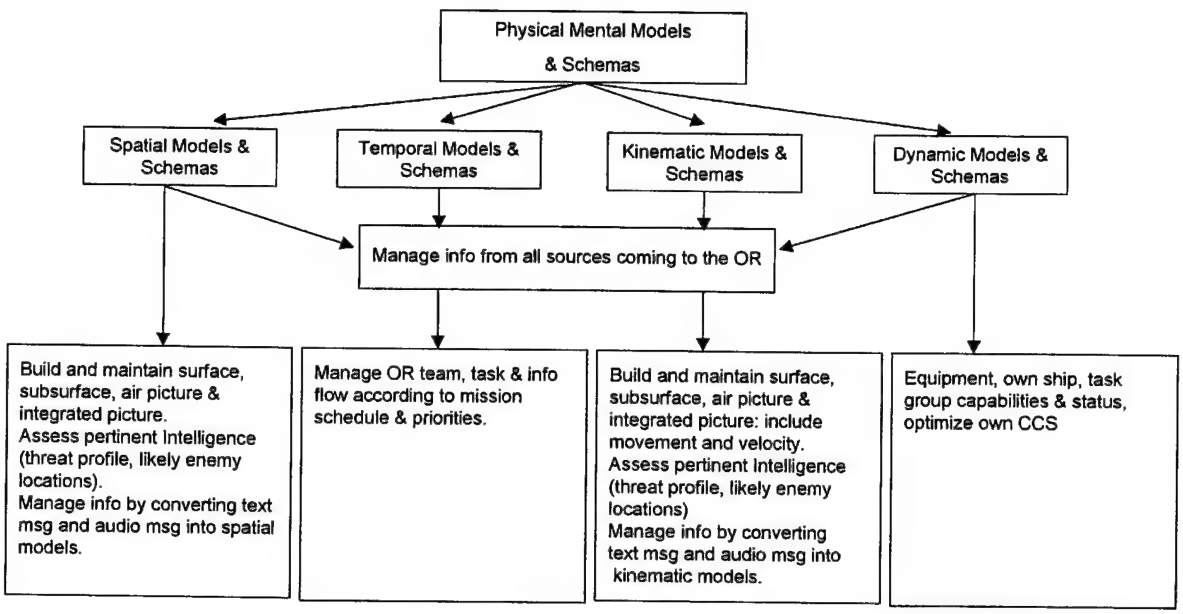


Figure 48. *Physical mental models and physical schemas include spatial, temporal, kinematic, and dynamic models (and schemas). Based on the Cognitive Task analysis of the OR awareness needs, the OR team members would construct spatial and kinematic models (and schemas) to represent and reason about different aspects of the air, surface, and subsurface environments. They would construct temporal models (and schemas) to represent and manage tasks and information flow according to mission schedule and priorities. They would construct dynamic models and schemas to represent and reason about physical systems whether at a small scale (e.g., equipment of ship) or large scale (e.g., task group capability).*

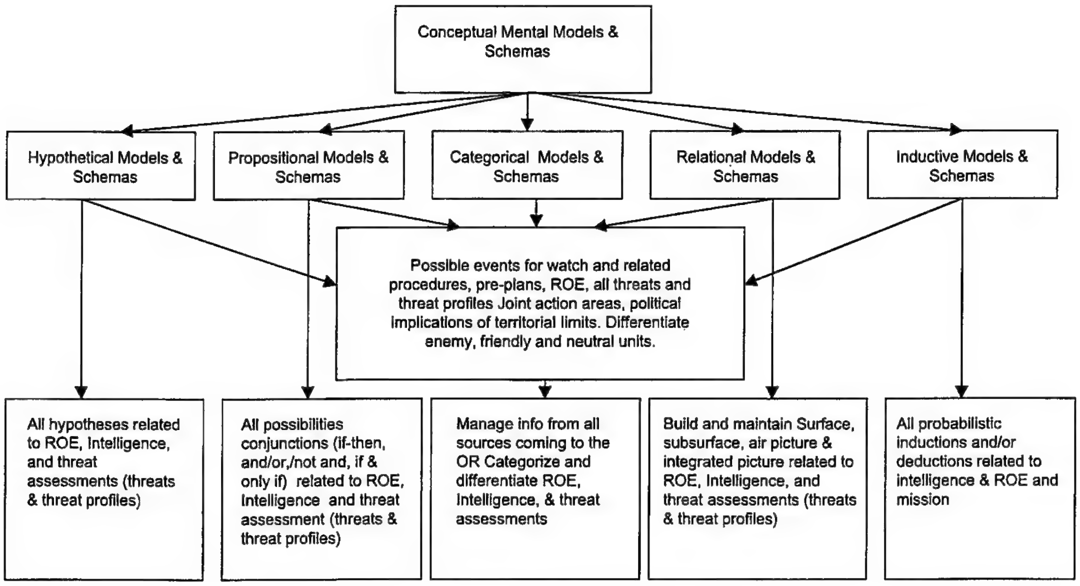


Figure 49. *Conceptual mental models and conceptual schemas include hypothetical, propositional, categorical, relational, and inductive models and schemas. Extensive experimental research indicates that humans build these mental models and schemas to represent and reason about hypotheses, possibilities, and probabilities (whether subjective or objective). It is most likely that the OR team construct these mental models and schemas to represent and reason about ROE, intelligence, and threats, whether these events for watch are hypothetical, possible, or probable.*

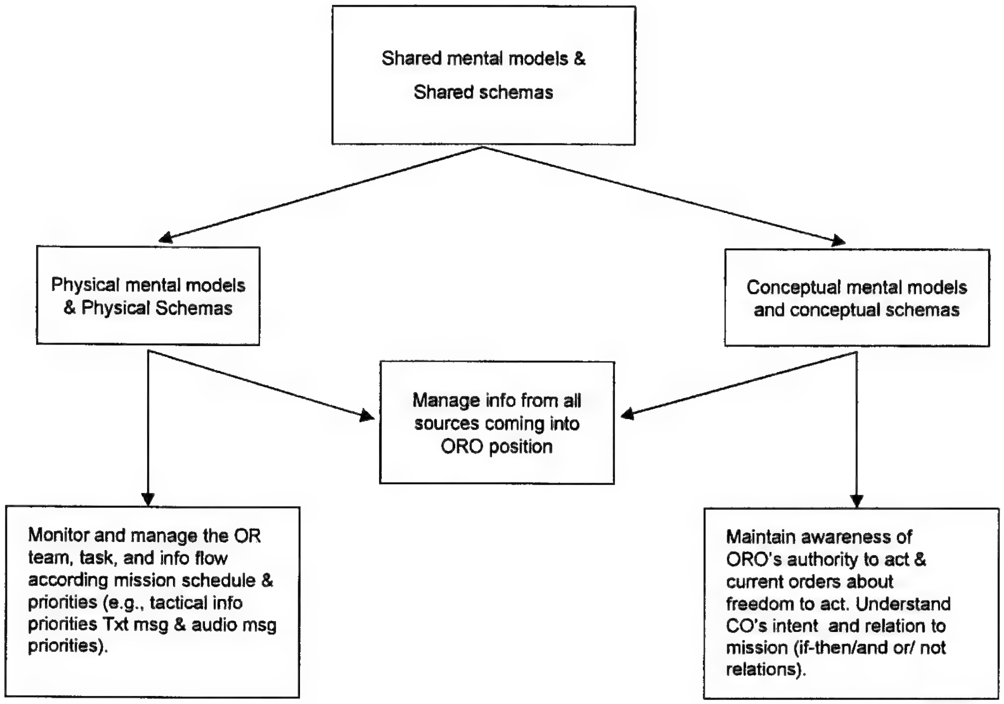


Figure 50. *All aspects of individual mental models and schemas are potentially shared among the OR team. Shared physical and conceptual mental models and schemas should apply to a subset of the awareness needs identified by The Cognitive Task Analysis (Matthews et al. (1999b).*

5. Role of belief biases and fallacies in reasoning

Mental representations include stereotyped beliefs that may have facilitative effects on situational awareness, reasoning and decision-making. However, stereotyped beliefs can also lead to biases and fallacies, that is, systematic errors. Belief biases are a priori beliefs about the truth of a conclusion (Evans, 1982, 1989). Belief biases affect human assessment of an argument's validity and the soundness of a decision (Evans, Over, & Manktelow, 1993). That is, humans will evaluate the validity of an argument based on prior beliefs rather than on the logical relations between the premises and the conclusion (Evans, 1989; Evans, Barston, & Pollard, 1983). According to Evans (1982, 1989; Evans, Newstead, & Byrne, 1993), when humans use a priori beliefs they will uncritically accept as believable fallacious arguments, that is, arguments that are logically invalid (see Figure 51 on the conflict between logic and belief).

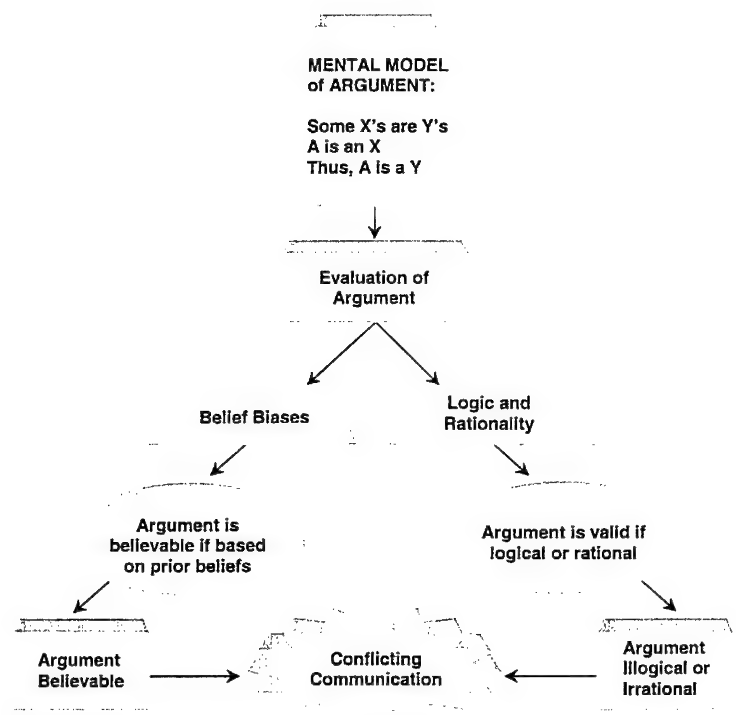


***Figure 51**. Humans can evaluate an argument based on a priori beliefs. An argument is believable if it is consistent with prior beliefs irrespective of the logic of the argument. However, humans can also evaluate an argument based on logical analysis. An argument is valid if it is logical or rational although it may not be consistent with prior beliefs. Conflicts in communication occur because humans evaluate arguments using either prior beliefs or logic and rationality.*

Fallacies are errors in human reasoning that occur commonly during discourse (Copi, 1990; Evans, Newstead, & Byrne, 1993; Johnson-Laird & Byrne, 1991). Deceptive generalizations constitute examples of fallacies. In such cases, humans reason to quickly from an instance to a general conclusion or from a general conclusion to an instance. From a cognitive perspective, fallacies are psychologically persuasive because humans typically believe their validity (Copi, 1990; Evans, 1989; Johnson-Laird & Byrne, 1991). Thus, belief biases and fallacies have important consequences in human reasoning and decision-making (Evans, 1989; Evans, Over, & Manktelow, 1993).

Cognitive scientists have proposed two main alternative models to account for the relations between logical reasoning and a priori beliefs: the *Selective Scrutiny Model* and the *Misinterpreted Necessity Model*. The Selective Scrutiny Model (Evans, 1989) argues that humans first determine whether a conclusion is believable, that is, consistent with a priori beliefs. If the conclusion is believable, they will have a strong tendency to accept it without analyzing the logic of the argument. Alternatively, if humans find that a conclusion is unbelievable, they will be more likely to evaluate the logic of the argument before making a decision concerning its validity. Evans and his collaborators (1989; Evans & Pollard, 1991; Evans, Barston, & Pollard, 1983) state that humans critically evaluate arguments or evidence that they do not agree with or which conflict with their own prior beliefs. They will do so even when the argument or the evidence is sound. Oakhill and Johnson-Laird (1985) have shown that humans are less likely to search for counterexamples if a conclusion is consistent with prior beliefs than if it is in conflict with such beliefs This tendency to selectively scrutinize is based on cognitive rather than on motivational factors. These cognitive factors pertain to the notion of cognitive economy whereby humans do not question claims that they already believe in.

The *Misinterpreted Necessity Model* (Diskstein, 1980, 1981) makes the opposite assumption to the Selective Scrutiny Model. The Model argues that humans first evaluate the logical validity of an argument in order to determine whether a conclusion is true or false. If they cannot ascertain the validity of an argument, they will then evaluate the argument based on its prior believability. Judgements of validity based on prior beliefs would occur for complex problems or for problems for which there is no valid solution.

The Misinterpreted Necessity Model (*op. sit.*) argues that the logical complexity of a problem directly affects the number of errors and the impact of belief biases on reasoning. Hence, as the difficulty of problems increases, humans would be more likely to resort to prior beliefs as heuristics to solve the problems especially when prior logical analysis does not yield a definite result. Complexity and belief biases would trade-off against one another: the more difficult problems would be more susceptible to belief biases. In contrast, the Selective Scrutiny Model (Evans, 1989) predicts that the effects of belief biases should be independent of the problem complexity. Rather, the main effect of belief biases would be the uncritical acceptance of believable conclusions prior to any analysis of the validity of an argument.

Evans and Pollard (1990) investigated the effects of problem complexity on belief biases. They showed, on reliable experimental grounds, the independence between problem complexity and belief bias. Their findings were also consistent with Evans's (1984, 1989) distinction between heuristics and analytical stages in reasoning. Evans (1984) has suggested that heuristic processes precede and can "preclude analytical reasoning processes". It is also the case for difficult areas of reasoning such as probabilistic reasoning (Tversky & Kahneman, 1982, 1983). It thus appears that subjects employ heuristics based on prior beliefs to selectively validate arguments.

6. Design issues

The foregoing review suggests that the OR team construct physical, conceptual, and shared mental models in memory in order to represent and reason about the physical environment (warfare areas), the social environment (military and political), and discourse among own/enemy units. Tactical displays should thus support each category of mental models to provide the best cognitive fit (Rasmussen, 1986; Vessey, 1991)

6.1 Supporting physical mental models

Experimental evidence on mental models supports data obtained from cognitive task analyses (Matthews et al., 1999a,b) that the OR team build mental models involving the spatial, temporal, kinematic, and dynamic properties of the warfare areas. Visual displays (sonar and radar) should thus facilitate the construction of these physical mental models. The OR Command row are required to create dynamic three-dimensional mental models of the warfare areas (illustrated in Figure 52). Visual displays should provide the necessary tools to construct such mental models. However, existing visual displays provide a two-dimensional scaled view of the different warfare areas.

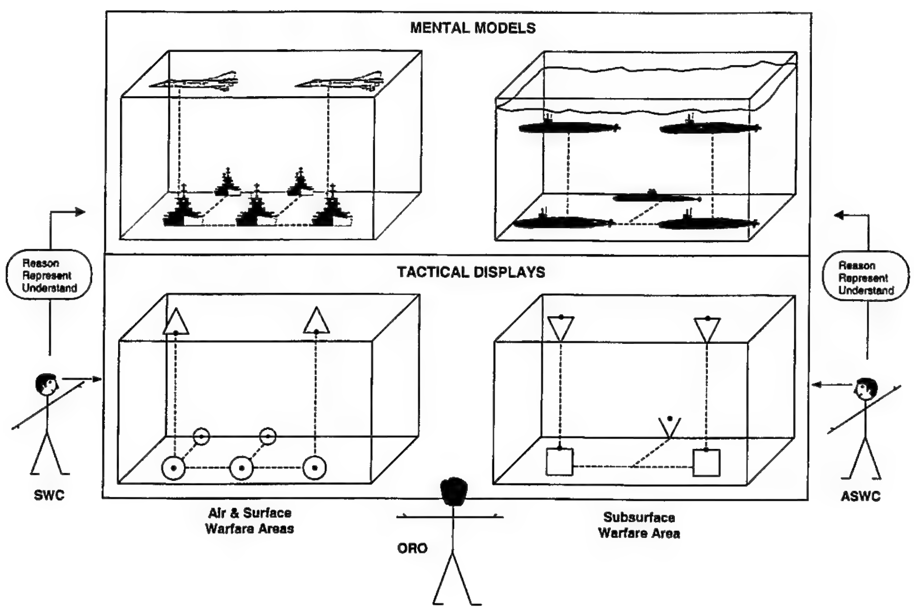


Figure 52. The SWC will construct a mental model of the surface and air warfare areas. The ASWC will construct a mental model of the subsurface warfare area. The ORO will build a mental model comprising elements of each warfare area.

6.1.1 Spatial models

It is particularly important, for at least two reasons, to display spatial relations in three dimensions. One is because the difficulty of constructing mental models increases with the number of dimensions in which entities are located in space (Boudreau et al., 2000; Boudreau & Pigeau, 2001). Another, which follows from the first, is that humans tend to create two-dimensional models from the information in two-dimensional displays, rather than spatial models that represent all three dimensions of space. (For this reason, subsurface issues are difficult to comprehend and visualize for the ORO (Matthews et al., 1999a, b)) Also, the use of image models to represent three-dimensional information yields viewer-centered representations that increase the mental workload required communicating accurate geometrical information. For example, using an image model, a person must change the viewpoint of the image by rotating the image or by changing reference frame. These are projective transformations that require formal reasoning (Boudreau et al., 2000). A three-dimensional spatial model and an absolute reference frame would reduce the mental effort required for such projective transformations. Thus, it would be more efficient to display three-dimensional spatial information in three-dimensions using an absolute reference frame (latitude, longitude and altitude).

The displays should also enable the OR team to construct physical models from verbal information which describe spatial relations. Physical models are easier to remember than verbal information because they represent the spatial structure of the relations among entities (Johnson-Laird & Byrne, 1991). Currently, the OR team have a significant overload of verbal descriptions of spatial relations. This overload increases the possibility of transposition errors when constructing a spatial model while slowing down the process of building such mental models. Information processing tools should thus support the transposition of sentences (such as A is left of B) into diagrams (such as A B). This transposition is important for two complementary reasons. First, the construction of physical models from text is more difficult than from diagrams because humans have to convert sentences into diagrams (Clark & Chase 1972) in order to construct physical models (Boudreau & Pigeau, 2001). Second, diagrams facilitate the organization of spatial models (Boudreau & Pigeau, 2001) and propositional models (Bauer & Johnson-Laird, 1993; Barwise & Etchemendy, 1992) and hypothetical models as reflected in economic trends (Tabachneck & Simon, 1992). In both cases, diagrams would systematically facilitate the construction of physical models.

6.1.2 Temporal models

The OR team members build temporal models of hypothetical situations in at least two cases. One is when they reconstruct past military situations and provide a causal explanation of these situations. Another is when they plan and project future tactical situations. Planning tools should support each of these aspects of temporal models.

6.1.3 Kinematic models

Simulated motion in visual displays is more effective than static motion cues in facilitating the formation of kinematic models (Park & Gittelman, 1995). Visual displays should support the construction of kinematic models by displaying movement of military

entities such as translation, rotations, and velocity. Visual displays should also simulate actual movement, non-visible patterns of movement (such as electronic flow), and movement of military entities projected from past movement, time-compressed if necessary.

About 30 years ago, when naval personnel used raw radar displays, errors in target detection could be reduced through time compression of visual data, that is, by visually time compressed radar displays. This technology provided a relatively continuous representation of coherent motion against background noise similar to the blossoming of a plant made apparent by time-lapse photography. For example, Scanlan (1975a, 1975b) and his colleagues (Scalan & Staton, 1973; Scalan, Roscoe, & Williges, 1971) demonstrated that visually time-compressed radar display would provide coherent motion cues that would *improve target detection* from noise and clutter on radar displays. The detectability of a target under conditions of increased noise and clutter improved due to time compression and the enhanced spatial aspect of the targets.

For synthetic radar displays, as currently in use, the problem of target detection from noise is no longer an issue. However, there would be definite advantages in displaying continuous motion of military entities through time compression. Over the last 30 years, however, very few studied have addressed the use of time compression for synthetic radar displays. Vidulich, Yeh, and Schneider (1983) used time-compressed simulation to aid the development of air-intercept control skills for air traffic control. These skills included identifying turn points and rollout headings for aircraft. The experiment involved two groups of subjects: one trained with a real-time simulation of the task, while the other trained with a time-compressed version of the task. The latter task ran about 20 times as fast as real-time trials. The authors then compared the efficency of the real-time and the time-compressed version of the tasks by testing both groups on real-time trials. Vidulich, Yeh, and Schneider (1983) indicate that time compression can be a useful technique for increasing the efficiency of training.

An other advantage of using time-compressed of motion cues would be to reduce *misassociated targets* in automatic tracker use (McFadden, Giesbrecht, & Gula, 1998). In automatic tracker use, the notion of misassociated targets refers to the confused identity of distinct targets whose spatial location overlaps at one point in time. For example, when the location of an enemy target overlaps with that of a friendly target, the identity of the former is confused with the latter and vice-versa. Using time-compressed motion cues associated with respective targets, the operator and/or the automatic tracker could keep track of the identity and location of the targets over time by referring, at will, to the information about the targets' motion.

6.1.4 Dynamic models

Mental models are intrinsically dynamic in the sense that humans revise them to adapt to the evolving tactical situation. The key factor in revising a mental model consists of integrating new entities and their relations to an existing mental model (Ehrlich & Johnson-Laird, 1982; Boudreau & Pigeau, 2001). This integration must occur in working memory. Given the limitations of working memory and the complexity of the warfare areas, mnemonic tools should assist the integration that occurs during the revision of

mental models. These mnemonic tools could, for example, visually simulate the different phases in the construction of a mental model. This issue invites investigation as there are no studies that have addressed the means by which to support the revision of mental models.

Mental models are also dynamic because they represent physical systems. Mental models of physical systems are important for the OR team members because they are required for awareness of equipment status. Malfunctions are generally unpredictable because the OR team may not have a schema of anticipated solutions. Therefore, the OR team must find creative solutions often under stress and time pressure. Dynamic models are essential for these tasks. Many scientific applications (such as architecture, mechanics, and biology) use three-dimensional displays to represent physical systems. These scientific applications may provide some insight on means to support naval personnel's mental models of physical equipment. We suggest that three-dimensional displays of complex physical systems (such as physical plants) should be represented hierarchically if ambiguity and clutter are a major problem. For example, the three-dimensional display would first represent the most important structural aspect of the system, and then it would allow the user to zoom into the component parts of the system. These component parts would also be represented in three-dimensions.

Mental models are also dynamic because they represent causal relations among the factors that may affect the structure and function of a physical system. Causal relations may consist of a set of factors that may have a necessary relation with an effect or that may covary with an effect. The OR team possibly constructs causal models of necessity and causal models of covariation for diagnostic reasoning. Visual displays and/or expert systems should thus support the OR team's capacity to reason about the necessary causal relations among events (or causes and effects). For example, expert systems could include a knowledge-base and inference engine supporting the three basic cognitive activities involved in causal reasoning: (a) the representation of factors that may cause a given event; (b) testing the effects of the factors and eliminating implausible ones using conditional rules such as "if p then q " and "if and only if X then Y"; and (c) deducing the most likely factor that may have caused an event. To visually illustrate the results of these processes, the expert system would display flowchart diagrams. For example, expert systems include such flowcharts to support medical or mechanical diagnostics.

6.2 Supporting conceptual mental models

In tactical displays, management tools should enable naval personnel to have access to three types of information. The first type of information should link each military entity of the tactical displays to an attribute-feature structure (for example, the type of enemy aircraft, speed, and altitude). For each warfare area, the OR officers should be able to query each military entity and obtain, below it, a menu of information regarding their attribute-feature structure. The second type of information should associate the military entities to a hierarchical structure; that is, it should link each entity to a type, a category, and a supercategory (see Figure 53). For example, the hierarchical structure could link the frigate to the type *military ship*. The hierarchical structure would reduce load on working memory because it would allow inheritance of attributes and relations of higher-level categories to lower-level ones. The third type of information should provide a complete view of the links between the different hierarchical structures within which the

military entities are embedded. These hierarchical structures would provide the global network of relations among military entities. One can imagine the global network as a set of hierarchical structures that are related to one another by various meaningful links. The OR team could then zoom in and out (Matthews, et al., 1999a) at will to any level of the global network. The team members could then alternate their level of focus and switch between higher levels and lower levels of an integrated mental representation. The latter assertion is one of the recommendations that Matthews, et al. (1999a,b) have from a cognitive task analysis of the OR team's activities.

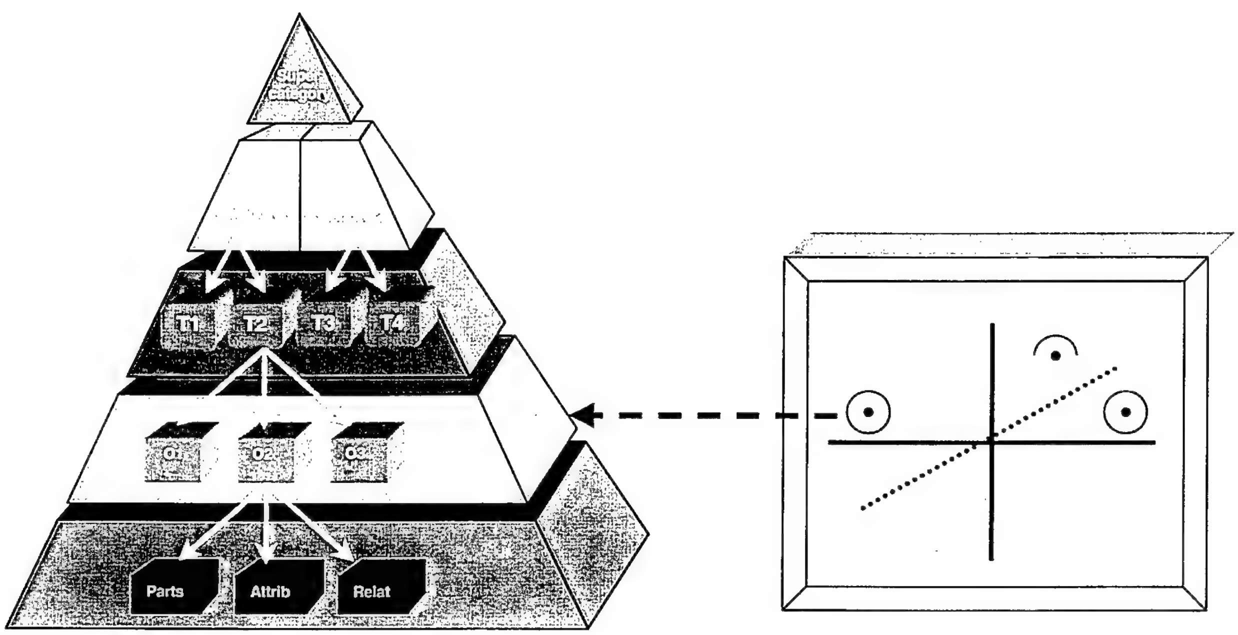


Figure 53. *Tactical displays should associate the military entities of the displays to a hierarchical structure of information; that is, it should link each entity to a type, a category, and a supercategory.*

6.2.1 Hypothetical models

The OR team constructs hypothetical models to account for unknown or uncertain events (see Figure 54). Knowledge-based and reasoning tools should be provided to help the officers generate hypotheses, verify hypotheses, and evaluate the most likely ones.

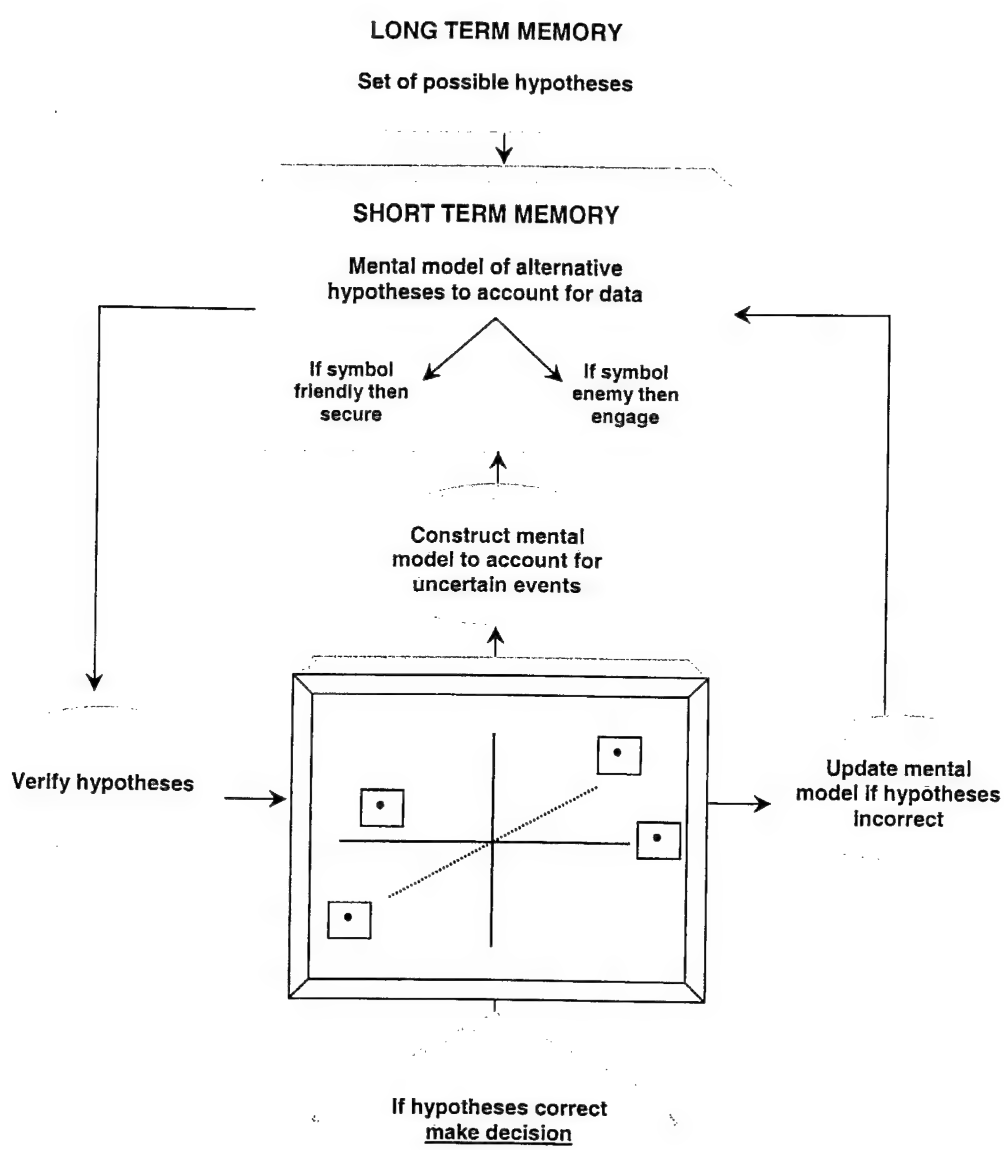


Figure 54. A set of unknown radar symbols will trigger the construction of a hypothetical model regarding the possible identity of the symbols. The hypothetical model can represent two hypotheses: (1) it is either a friendly target, or (2) it is an enemy target. Humans will verify these hypotheses based on observed stimuli. If the hypotheses are correct, these will provide a basis for taking decisions. If the hypotheses are incorrect, humans will construct hypotheses that are more plausible.

6.2.2 Propositional models

Propositional models enable OR personnel to represent and reason about alternative situations that arise when they are coping with uncertainty. For example, alternative situations can consist of potential courses of action. Propositional models apply to spatial contents such as potential courses of action (e.g., either the Bear will engage the F-14 *or* the Mig will engage the F-14) and non spatial contents such as assertions regarding the identity of unknown units (e.g., either X is an enemy unit *or* X is a friendly unit). Studies have shown that diagrams can improve the visualization of alternative situations (e.g., Bauer & Johnson-Laird, 1993). Although few studies (e.g., Bauer & Johnson-Laird, 1993) have addressed this issue, the studies indicate that there are definite advantages of visually supporting propositional models.

6.2.3 Categorical models

The Mental Models theory argues that humans construct three types of categorical models: (a) set models, (b) set-theoretic models, and (c) meta-theoretic models (Johnson-Laird, 1983). These categorical models assume that humans organize information according to a generalization hierarchy. Matthews et al. (1999a,b) also suggest that the OR team use such generalization hierarchy in representing spatial and non-spatial information. Although scientists have not yet determined whether humans actually visualize categorical models, and how they do so; visualization tools may help support the construction of such mental models. In the case of set models, these tools could consist in Venn Diagrams (shown in Figure 42), sets (see Figure 43) or hierarchical structures (illustrated in Figure 53).

Set-theoretic models and meta-theoretic models still remain the subject of scientific inquiry. These mental models are the most abstract of categorical models. Although abstract, they are capable of representing generically complex sets of entities using the minimum of symbolic tokens. For example, the symbolic token A can include three sets {a, b, and c} each of which may stand for multiple entities. Thus, set-theoretic models and meta-theoretic models would provide very efficient and economical ways of representing complex sets of entities in memory (short-term and long-term). Given these advantages, it would thus be profitable to investigate how humans construct these categorical models and how visual displays could aid their representation.

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7. Discussion, conclusions, and recommendations

One of the major findings of this literature review is that cognitive studies on mental representations and reasoning processes have evolved independently from studies on naval operations. Furthermore, the literature on mental models and schemas provides very few links in either experimental or applied research (Matthews et al. 1999a, b). Strictly speaking, we can make recommendations for improving tactical displays only by extrapolating the findings of cognitive science to the OR team's activities. In order to guide future research, we propose the following priorities.

There is a definite requirement to pursue further research on *the nature of mental representations and reasoning processes underlying naval operations*. For example, one question would be to determine in a multi-threat scenario (e.g., air and surface) how the ORO integrates the different warfare areas, and what are their structure and content. Maintaining multiple mental models would increase mental workload whereas an integrated mental model would have the advantage of representing the structure of the global picture. However, because of its complexity, the integrated mental model will require a high level organization of the content and level of detail of the different warfare areas. Moreover, when naval officers think about a problem do they use mental models only to represent information in short-term memory, or do they store mental models in long-term memory in order to regain access to them? How do naval commanders deal with the mental workload associated with constructing integrated mental models (and/or schemas) of all warfare areas?

7.1 Theoretical issues

7.1.1 Situation awareness

Cognitive scientists have linked schemas and mental models to the concept of situation awareness (see Endsley, 1995, 1997). Mental models, however, provide a more accurate account than schemas of the relations between perceiving events, understanding them, and representing them in short-term memory (see for example, Figure 47). Given experimental evidence, mental models represent the essential aspects of a situation, that is, the relevant entities, their attributes, and their relationships (see for example, Johnson-Laird & Byrne, 1993). Schemas also provide, through selective sampling, a basis for understanding a situation. However, Schema theories (Anderson, 1995; Norman & Rumelhart, 1975; Rumelhart, 1980) have yet to determine the processes by which humans form situation awareness from schemas.

7.1.2 Memory

Humans can construct mental models and schemas in short-term memory to represent physical and conceptual information. However, the focus of research on schemas has been on the representation of information in long-term memory. Very few studies (Dutke, 1996) have investigated how humans construct schemas in short-term memory to represent and solve problems. In contrast, the focus of research on mental models has

been on the representation of information in short-term memory. Further studies should address the organization of mental models in long-term memory. Moreover, Schema theories (Anderson, 1995; Norman & Rumelhart, 1975; Rumelhart, 1980) and the Mental Models theory (Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991, 1993) have yet to specify the relationships among schemas and mental models especially for complex situations.

7.1.3 Reasoning and decision making

Mental models and schemas are essential for reasoning. However, since the Mental Models theory has repudiated the Formal Rules theories' proposal, scientists have interest in accounting for the processes by which humans make inferences from schemas.

Scientists have related the concept of schemas to decision making, namely to recognition-primed decision strategies. These decision strategies involve matching attributes (and features) of an entity (e.g., object or situation) to those of schemas, or matching an entity to the prototype of a schema (Klein, 1989). The Mental Models theory has also linked mental models to descriptive forms of decision-making (e.g., intuitive decisions) rather than prescriptive ones (e.g., analytical decisions) (Johnson-Laird, 1995). A question would be to determine the relationships between mental models and schemas during decision making.

7.2 Experimental issues

7.2.1 Physical models and schemas

7.2.1.1 Spatial models and schemas

A research issue pertains to the mental representation and processes of spatial reasoning in perspective. This type of formal reasoning, which has not yet been investigated, involves constructing spatial models in different perspectives and reasoning from them in different perspectives. Another research issue pertains to the effects of linguistic and physical orientation cues on these mental representations and reasoning processes. A further issue addresses the effect of different types of reference frames (e.g., intrinsic, relative, and absolute) on the mental representation and processes of spatial reasoning in perspective. For example, the use of reference frames in changing perspective ("ranging in" and "ranging out") with a tactical display. These three issues may have implications for the scientific and military understanding of spatial cognition during naval and air navigational operations. There are also research and training issues related to the memory required for accurate mental models, communicating them, and switching between local and global picture (Vandierendonck & De Vooght, 1996). A research issue related to the design of tactical displays consists of determining the best spatial configuration of the human-computer interface. One should first test whether to present a single screen integrating all warfare areas or present displays of the different environments simultaneously on adjacent displays. Second, one should also determine the best configuration

of future computer displays: use either a circular array or a rectangular array. Finally, scientists should investigate large-scale spatial models of the air, surface, and subsurface environments.

7.2.1.2 Temporal models and schemas

The OR team members build temporal models of hypothetical situations in at least two cases. One is when they reconstruct past military situations; another is when they plan and project future tactical situations. Given the relevance and importance of temporal models, scientists should determine the way in which the OR team construct, represent, and reason about temporal models of hypothetical situations.

7.2.1.3 Kinematic models and schemas

Matthews et al.'s (1999a, b) cognitive task analysis also supports the assertion that kinematic models are important for the OR team members because they are required to represent movement and relative velocity of the air, surface, and subsurface units. However, there are very few studies that have investigated kinematic models (see Freyd, 1983; Park & Gittelman, 1995). An initial research issue is to determine how the OR team represents and predicts movement of military units that are within and out of radar range. For example, from the given path of a military unit and knowledge of its intention, how well can humans represent and infer the future path of the military unit? A second research issue is to determine how humans represent and reason about movement related to oceanographic conditions and weather conditions. Kinematic models of such conditions are important to consider when the OR team members are planning navigation paths of military units for the different warfare areas. Another issue is to address the use of time compressed simulations to aid the development of control skills such as those used for air intercept control (Vidulich, Yeh, & Schneider, 1983) given that the foregoing is virtually the only study on the subject.

Another issue is to use time-compressed motion cues to determine the extent to which these cues reduce *misassociated targets* in automatic tracker use (McFadden, Giesbrecht, & Gula, 1998). This review endorses the prediction of McFadden et al. (1998), that in using time-compressed motion cues associated with respective targets, the operator and/or the automatic tracker could keep track of the identity and location of the targets over time by referring, at will, to the information about the targets' motion.

7.2.1.4 Dynamic models and schemas

A research issue is to account for the processes by which humans revise mental models in addition to creating computer models of such processes. Mental models of physical systems are important for the OR team members because they are required to maintain equipment and deal with emergencies such as major malfunctioning caused by enemy action. However, the nature of these

dynamic models raises three issues that invite investigation. A first issue is to determine the type of dynamic models that the OR team construct in normal and emergency situations. A second issue is to determine how best to display mental models of physical equipment without cluttering the visual field or overloading human memory. A third, issue is the nature of the causal models that the OR team use during command operations either in normal and/or emergency situation.

7.2.2 Conceptual models and schemas

7.2.2.1 *Hypothetical models and schemas*

Hypothetical models consist of a set of hypotheses that humans generate automatically in response to uncertain, possible, probable, or novel events (Bruner, Goodnow, & Austin, 1956). How do the OR team members construct hypothetical models of uncertain, possible, and/or probable events? How are these hypothetical models used to create alternative courses of action relative to possible enemy courses of actions. These issues have not yet been the investigated.

7.2.2.2 *Propositional models*

We have made the hypothesis that the OR team members build propositional models to represent and reason about alternative possibilities or hypotheses that they generate when coping with uncertainty (Johnson-Laird, 1994a, b; Johnson-Laird & Byrne, 1991; Johnson-Laird, Byrne, & Schaeken, 1992; Shafir, 1994). Representing and reasoning about alternatives is very relevant for understanding, anticipating, and reasoning about an adversary's strategy and tactics. Propositional models are also an essential basis for creating and imagining different tactical scenarios. Future studies should thus address the way in which humans and in particular the OR team, create alternative possibilities and reason about these alternatives.

7.2.2.3 *Categorical models*

The OR team members are required to categorize sets of entities from stimuli presented on tactical displays. The OR team can identify categories of entities using categorical models. These mental models assume a hierarchical structure of semantic knowledge that is increasingly generic. There are three types of categorical models: (a) set models, (b) set-theoretic models, and (c) meta-theoretic models (Johnson-Laird, 1983). Matthews et al., (1999a) have observed, from their cognitive task analysis, a similar structure of semantic representations. Categorical models could provide very efficient and economical ways of representing complex sets of entities in memory (short-term and long-term). Given these advantages, it would be profitable to investigate how humans construct these categorical models and how visual displays could aid their representation. Moreover, human-computer interface

designers have been proposed different ways to represent categorical structures. However, the efficiency of these displays in facilitating human performance has yet to be shown.

7.2.2.4 Relational models

Relational models are important when the OR team members are constructing physical models of space, time, movement or causality (Matthews et al. 1999a, b). For example, a spatial model can specify the relative location of entities according to spatial relations such as in front, above, and left. To date, studies on relational models have pertained to space (Boudreau & Pigeau, 2001; Boudreau et al., 2000). To our knowledge there are very few, if any, studies on relational models of time, movement, and causality

7.2.2.5 Inductive models

When humans draw a conclusion without considering counter-examples, they will base their belief in the conclusion on a priori biases and heuristics (Evans, 1989). The search for counter-examples (for inductions or deductions) is also an essential aspect of creative and inventive thinking. However, there are at least three factors that constrain the consideration of counter-examples: (1) the processing capacity of *working memory*, (2) the *availability of relevant information*, and (3) the propensity of humans to be *inferential satisficers.* Given the consequences of errors and biases in naval operations and in human judgements in general, future studies should investigate means of developing or enhancing the search for counter-examples to mitigate the constraining effects of the above three factors.

7.2.2.6 Analogical models

Analogical models will help the OR team recognize the similarities between a current tactical situation and categories of pre-planned courses of actions. These similarities will then provide a basis to solve problems regarding the actual tactical situation. Despite the importance of analogical models in naval command, no study has yet investigated how the OR team members construct these mental models and reason from them.

7.2.3 Shared mental models

A core concept that underlies good teamwork is that of shared mental models (see Figure 55). Despite the importance of physical and conceptual mental models in teamwork, there is a systematic paucity of research regarding the use of these mental models in team performance. One issue that scientists should investigate is the systematic development of *shared physical and conceptual mental models* as a framework for training a team of experts into an expert team. Another would be to determine how to support team performance by simulating the decision-making behavior of the team of experts. A fourth issue that calls for investigation pertains to mental models of intentions because these are

essential for communication and reasoning about the enemy's possible and probable courses of action.

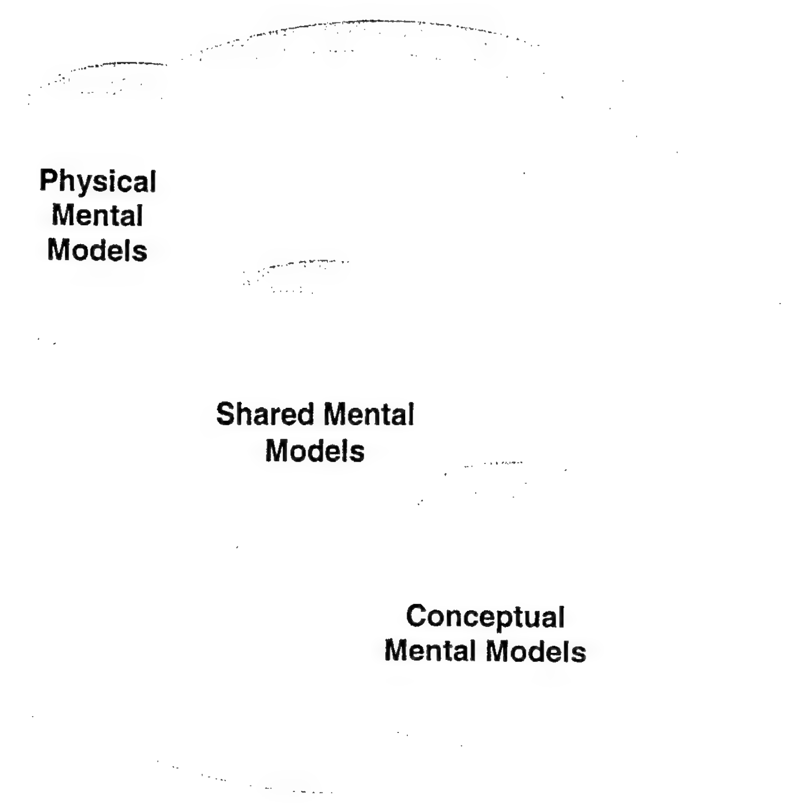

Figure 55. Future studies should investigate conceptual mental models and physical mental models within a teamwork environment

7.2.4 Belief biases and fallacies in reasoning

There are various research issues pertaining to belief biases that invite investigation. A very general research issue is to determine the effects of prior beliefs on team cognitive processes. One question regarding such effects is to determine whether belief biases are tempered within a team, or whether they are shared and reinforced among team members. A second issue is to determine the effects of stress and mental workload on belief biases. For example, in high stress and time pressure, it may be easier to infer a conclusion based on prior beliefs even if in error rather than consider counter-examples to a conclusion. A third issue is to use scientific knowledge of belief biases and fallacies as basis to create deception schemes for information operations.

7.3 Design issues

From the discussion in Section 6, a number of design recommendation may be based on the OR team's awareness needs and the generic aspects of human mental representations, that is, mental models and schemas.

7.3.1 Physical mental models and schemas

7.3.1.1 Spatial models and schemas

- Multi-sensor data fusion systems should support situation assessment, mission planning and navigation. A key factor in the integration process is the ability to build and maintain spatial models of the surface, subsurface, and air environments using spatial database management systems.

- Data and information pertaining to the air, surface, and subsurface environments should be represented using a spatial database management system (SDBMS). The SDBMS structure should be hierarchical, semantic and object-oriented. These SDBMS can deal with highly voluminous spatial database and complex search requirements.

- SDBMS should be hierarchical to reduce search space size and improve cognitive performance. The spatial database structure could consist of a pyramid quadtree. The pyramid structure provides a uniform hierarchical spatial representation that supports the structure of human semantic representation both within a category of objects (or features) and between categories of objects.

- For situation awareness, incorporate relevant geographical information of the external environment from the start on the watch. Include information relevant to weather, sea state, visibility, cloud cover, moon phase, visible ships, and coastline.

- Include surface, and/or air contacts within sensor or weapon range of ship range; current contact status (friendly, enemy, neutral, civil), zones (channels, traffic pattern, territory limits), hazards (wrecks, shallows, etc.), threat profiles, relative weapon ranges, pertinent intelligence (threat profile, likely enemy locations, etc), for air contacts include zones (air lanes, traffic patterns, oil hellos) territorial limits, coastlines, related navigational hazards, and tactical limits (minefields, weapon ranges own and enemy

- For subsurface environment, include potential subsurface contacts (e.g., mines, submarines, torpedoes, obstacles), underwater topology (e.g., obstacles, currents, thermal conditions that affect underwater sensors), no go zones (e.g., joint action areas, sub action areas, territorial limits) political implications (see deductive models for political implications), and location of underwater surface noise (e.g., engine, weapon range, own and enemy, etc.)

- Build multi-dimensional integrated models (and schema) of relevant warfare areas. Construct integrated models (and schema) including important relations and features of all warfare areas but at limited level

of detail and according to importance. Include ship capability, related threat profiles, ROE.

- Integrate warfare areas. Integrate changes to the tactical situation and update picture for all warfare areas. Update spatial databases using techniques of non-monotonic reasoning (Brachman, Levesque, & Reiter, 1989) and spatial reasoning (Boudreau & Pigeau, 2001). Keep track of the tactical situation as it is unfolding and allow for playback.

- Assess pertinent Intelligence from spatial information (e.g., threat profile, likely enemy locations, and distances).

- Detect, integrate, and recall the various surface, subsurface, or air factors that may affect the ship and/or TG in the conduct of the mission.

- Manage information by converting text messages and audio messages having a spatial component into spatial models. Allow the OR personnel the possibility to select preferred mode of information display (e.g., text, audio, visual).

- Enable the OR team to maintain awareness of the global and local picture; to zoom in or out of any given picture (in terms of time, or range, bearing, hierarchical structure). Allow the OR team to switch attention to changing pictures and to navigate the warfare areas at different levels. Determine the configuration (spatial disposition, relative size) of the global picture relative to local area of interest.

7.3.1.2 Temporal models and schemas

- Develop expert systems to manage information from sources coming into the OR position according to mission and tactical priorities; to establish schedule of anticipated events for all phases of naval operations. Specify routine events (report deadlines, incoming reports), special events (flying program, conferences), mission events (pre-planned actions, threat assessment, and threat response).

- An expert system should monitor the OR team in terms of scheduling tasks. The expert system should also prepare check list to monitor progress on required action items during watch, watch handover information, Sitreps to ORO, current mission goals, OR tasks to be done, tasks in hand, task schedule, critical path, OR resources available, Air Tasking Order (ATO), Task Group program, airline schedules.

- An expert system should reconstruct mental models (and schemas) of past military situations whether actual or hypothetical and obtain a simulated visual display of the situation as it did occur or as it might

have occurred. Relate simulated visual display of past military situations to an automated causal analysis of the situation.

- An expert system is required for constructing temporal models (and schemas) of future tactical situations whether hypothetical, possible, and/ or probable. The expert system should also project temporal models (and schemas) into the future to support navigational issues and tactical decisions. OROs should be able to enter parameters of a tactical situation (all relevant factors and history pertaining to own and enemy forces), and obtain a simulated visual display of the unfolding of future tactical situations and their outcome. Provide automated counter-examples to what the OR team would envision as the most likely or probable enemy situation.

7.3.1.3 Kinematic models and schemas

- Display movement of military entities such as translation, rotations, and velocity. Simulate actual movement, non-visible patterns of movement (such as electronic flow), and projected movement of military entities from given path. Simulate and display continuous motion of military entities, namely submarines and ships, through time compression. Distinguish identity of units using history of their path to reduce *misassociated targets* in automatic tracker use.

- Detect pertinent changes to warfare areas and update kinematic model (and schemas) using techniques such as non-monotonic reasoning for database revisions.

- Assess intelligence (all threats and threat profiles) using spatial-temporal parameters such as location, velocity, distance, navigation path, and angle of motion relative to own ship. Present spatial-temporal parameters in visual form (e.g., actual visual location) as well as in metrical form (e.g., latitude and longitude, or altitude). Identify and track hostile contacts beyond own sensors, weapon range and awareness time.

- The operator-machine interface should simulate the hypothetical kinematic models that the ORO will imagine and project to support navigational issues and tactical decisions for the surface, subsurface and/or air warfare areas.

7.3.1.4 Dynamic mental models and schemas

- Represent and maintain model of equipment capabilities, own ship, Task Group capability, and status and tactical significance of any shortfall. For complex equipment, display structural components.

- Represent complex physical systems (such as the engine room) as a hierarchical structure in three dimensions that the OR team can explore at different levels of the hierarchy.

- For each member of the OR team, optimize CCS display, CCS settings (e.g., brightness), mission settings or requirements (e.g., notes on pre-plans, ROE, information layers, oceanographic information layers), technical settings (e.g., procedure, cheat sheets, alarm settings needs).

- Display problems of major systems (sensors, weapons, EW, Helo, etc.) and effect on OR performance, priority and schedule for repair.

- Provide expert system to generate most likely repair solutions for equipment malfunction or damage that tends to be unpredictable, and have automated repair assistance for emergencies.

- Construct expert systems for causal reasoning to enable diagnostics of any relevant aspect of the tactical situation. The expert system should (a) represent knowledge relevant to a given event, (b) the factors that may cause a given event; (c) test the effects of the factors and eliminate implausible factors, and (d) infer the most likely factor (or the factors) that has caused an event. Visually present the results of these processes (e.g., flowchart diagrams).

- Spatial expert system and database should keep track of the OR team's evolving mental models (and schemas) of the dynamic situation, their mental model of physical equipment, and their causal model. Mnemonic tools should assist the integration of the different warfare areas.

7.3.2 Conceptual models and schemas

7.3.2.1 Hypothetical models and schemas

- Construct and display hypothetical models (and schemas) to account for unknown or uncertain tactical events. Apply hypothetical models to any physical or conceptual model (or schema). For example, apply hypothetical models to kinematic models in order to generate possible kinematic models. Generate hypotheses and outcomes as they relate to pre-plans, procedures, ROE, intelligence, and threat assessments. Simulate the visual outcomes of hypothetical models, verify and/or evaluate the most likely ones.

- Provide automated intelligence analyses to update and maintain pertinent intelligence (threat profile, likely enemy locations), differentiate friendly, enemy, and neutral units. Update any hypotheses related to intelligence or changes in contact status or

tracks. Keep track of territorial limits in air, surface, and subsurface areas, and their political implications.

7.3.2.2 *Propositional models and schemas*

- Provide propositional models for creative thinking and reasoning under uncertainty, representing possible alternatives (or, and, if and or, not) and their combinations as they relate to the different warfare areas, ROE, intelligence and threat assessment. Construct alternatives for any physical or conceptual mental model (or schema). For example, build alternative kinematic models of air navigation paths.

- Display visual representations of alternative tactical situations. Visually display the alternatives of propositional models whether they apply to spatial contents such as potential courses of action (e.g., possible engagements) or non spatial contents (e.g., authority to act with respect to rules of engagement).

- Develop expert systems to maintain awareness of ORO's authority to act, the CO's current orders about freedom to act (known limits to own authority to act independently of any superior authority), current ROE, changing ROE, and represent how limits of authority are changed by circumstances. Apply propositional reasoning (If-then, or, not, if and only if) in relation to the CO's intent, mission, and ROE.

7.3.2.3 *Categorical models and schemas*

- Organize relevant information coming to the OR according to the hierarchical structure of semantic categories (schemas and mental models),

- Apply the generic attribute-feature structure, generalization hierarchy, partitions, and constraints relevant to schemas. Allow inheritance of attributes and relations of higher-level categories to lower-level ones.

- Apply the structure of categorical models by visually representing the relations between categories (for example: mutually exclusive sets, intersecting sets, embedded sets).

- Generate categorical models that contain a finite set of generic tokens and relations that can represent implicitly large and complex sets of entities (for example, generic symbols such as those used to represent military units).

- Display a complete visual representation of the links between the different hierarchical structures within which military entities are embedded. These hierarchical structures would provide the global

network of the relations (geographical and tactical) among categories of military entities.

- Display menus to query each military entity and obtain, for each, a menu of information regarding their attribute-feature structure, generalization hierarchy, and its relation to all other categories of information.

- Conceptual databases should integrate information from all sources coming to the OR.

- Organize and represent auditory traffic and text traffic content, mission priorities, and tactical priorities.

- Organize and represent relevant information from the air, surface, and subsurface warfare areas in an integrated representation.

- Organize and represent categories of equipment capability including weapons, sensors, ship manoeuvre, and personnel.

- Ensure access to information available (confirming evidence, disconfirming evidence, correlation evidence); disconfirming evidence (and counter-examples) should be required to classify information contact unambiguously (Matthews et al., 1999b).

- Display potential error source (sensor limits, ambiguous data, and team co-ordination).

- Represent the OR team's knowledge for coming on watch from relevant information. Check for any factor affecting ship or Task Group capability, sensors, weapons, mission plans, schedule for watch, decision context, ROE, enemy threat profile.

- Update understanding of threats and threat profiles, ROE, changes to above since last watch, significance for mission. Differentiate, identify, and categorize ROE, intelligence, threat assessments, and changes in contact status or tracks.

- Allow the OR team to zoom in or out of a hierarchical structure of information (spatial or non spatial) for the local and global picture, and to change the spatial-temporal scale of any given picture (zoom in or out in terms of time or range and bearing to a new contact)

- Display warfare areas to allow attention to switch easily between different warfare areas, between the global and local warfare areas, or the local to local aspects of the warfare areas. Establish linkages among all three warfare areas.

7.3.2.4 *Relational models and schemas*

- Build and maintain spatial database of relations among the entities of the surface, subsurface, and air picture as they relate to ROE, intelligence, and threat assessments.

7.3.2.5 *Inductive models and schemas*

- Represent probable courses of action of own and enemy units, pre-plans, ROE, all threats and threat profiles, joint action areas, and political implications of territorial limits.

- Compile inductive conclusions or decisions related to intelligence, ROE and mission. Assess likelihood of conclusions or decisions.

- Present counter-examples to attenuate the effects a priori biases and heuristics on reasoning and decision making. Counter-examples should be provided even if all evidence seems to confirm a given conclusion especially for situations where decisions must be taken rapidly and in high stress.

7.3.2.6 *Analogical models and schemas*

- Construct sets of analogical models (and schemas) for rapid problem solving and decision making during emergencies.

- Construct analogical models (and schemas) to support any other cognitive process or mental models involved in naval operations. For example, apply analogical models (or schemas) for diagnostics or creative problem solving of equipment malfunctioning.

7.3.3 Shared mental models

7.3.3.1 *Shared mental models and schemas*

- Represent and display the CO's intent and relation to mission and ROE using propositional relations (if-then/and or/ not relations).

- Monitor awareness of the ORO's authority to act and current orders about freedom to act without reference to superior authority.

- Represent ROE, factors changing ROE, and how they affect the ORO's freedom of action.

- Maintain database of information that is relevant and related to the OR team's shared mental models. Tactical displays should allow the OR team to visualize the team's common knowledge requirements of

the tactical environment, the team role structure, the task, and the mission. The displays should allow the OR team to access and visualize common requirements pertaining to physical models and conceptual models.

- Monitor and manage organizational behaviour of the OR team, task, and info flow according mission, CO's intent, CO's order book, mission schedule and priorities (e.g., tactical information priorities).

- Construct and display temporal models (and schemas) to balance the OR team's various priorities in parallel for multiple tasking. Visually display critical timeline path for tasks along way to achieve tactical goal, anticipate problems and meet deadlines.

- Represent in spatial database planning scenarios and implement automated matching procedures to allow the OR team to rapidly select the most feasible plan during threat assessment or threat response.

7.3.4 Next steps

- Using our scientific knowledge of human cognition, establish a set of criteria that scientists can use to evaluate the USN TADMUS DSS operator-machine interface.

- Investigate, in the existing Human Computer Interaction literature, existing software on schemas and mental models (e.g., Staggers and Norcio, 1993) to determine if and how the software could be used in the design of tactical displays of the CPF.

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9. List of abbreviations

Abbreviation	Meaning
ASWC	Assistant Sensor Weapons Controller
C2	Command and Control
CO	The ship's Captain as the commanding officer
CbtO	Combat Officer
CCS	Command and Control System
CIO	Combat Information Organization
ChO	Chambre D'Opérations
DND	Department of National Defence
HCF	Halifax-class Frigate
NCM	Non-commissioned Member
OR	Operations Room
ORO	Operations Room Officer
SA	Situation Awareness
SAC	Surveillance Aircraft Controller
SWC	Sensor Weapons Controller
RT1	Response Track 1
RT2	Response Track 2

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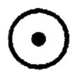
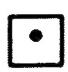
10. List of symbols

Symbol	Meaning
	Air Friendly
	Friendly Surface
	Subsurface Hostile
	Air Hostile Engaged
	Subsurface Friendly Engaged
	Air Hostile
	Surface Unknown
	Air Unknown
	Subsurface Unknown

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14. ABSTRACT

(U) The objective of this study is to review relevant theories and research pertaining to the fundamental mental representations that are common to humans in general and, in particular, to naval operations. The review will focus on the mental representations of the Operations Room (OR) team aboard the Halifax-Class Frigate (HCF). We will specify the structural, organizational, and functional properties of these mental representations. The practical aim of the review is to provide recommendations concerning the design of the tactical displays of the air, surface, and subsurface warfare areas.

The integration of relevant theories and research has enabled us to formulate the principle hypothesis according to which the OR team constructs three categories of mental models: physical mental models of the physical environment (such as warfare areas), shared mental models of the social environment (own and enemy units), and conceptual mental models of discourse among own and enemy units. We have based this hypothesis on the assumption that the OR team must represent and reason about the physical environment, the social environment, and discourse among own and enemy units. The results of this review suggests that all three categories of mental models are important for the OR team members. Tactical displays should thus support each category of mental models to provide the best cognitive fit, that is, to accurately match the mental representations of the OR team members.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) Mental representations;mental models; schemas; formal rules;situation awareness;memory; creative thinking, reasoning; uncertainty; decision making; naval command; naval operations; Operations Room team; naval tactical displays; human-computer interfaces;knowledge representation; expert systems

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